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Content

Environmental Geology

1. Introduction

People today may be more concerned with our environment that ever before since the Industrial Revolution. We have come to realize that, while we are generally better off now, rapid increase in world population and development of resources is straining our planet's natural support system. We are concerned about global warming, energy supply, water resources and pollution of our air, water, and land. We are struggling with how to provide a future for our children that will include a high-quality environment with sufficient space for people as well as the incredible diversity of life with which we share our planet. In short, we are struggling to develop what we term "sustainability".

What is environmental geology?

Geology is the science of processes related to the composition, structure, and history of Earth and its life. Geology is an interdisciplinary science, relying on aspects of chemistry (the composition of Earth s materials), physics (natural laws), and biology (understanding of life-forms).

Environmental geology is applied geology. Specifically, it is the use of geologic information to help us solve conflicts in land use, to minimize environmental degradation, and to maximize the beneficial results of using our natural and modified environments. The application of geology to these problems includes the study of the following (Figure 1):

1. Earth materials, such as minerals, rocks, and soils, to determine how they form, their potential use as resources or waste disposal sites, and their effects on human health.
2. Natural hazards, such as floods, landslides, earthquakes, and volcanic activity to minimize loss of life and property.
3. Land evaluation for site selection, land-use planning, and environmental impact analysis.

4. Hydrologic processes of groundwater and surface water to evaluate water resources and water pollution problems.
5. Geologic processes, such as deposition of sediment on the ocean floor, the formation of mountains, and the movement of water on and below the surface of Earth, to evaluate local, regional, and global change.

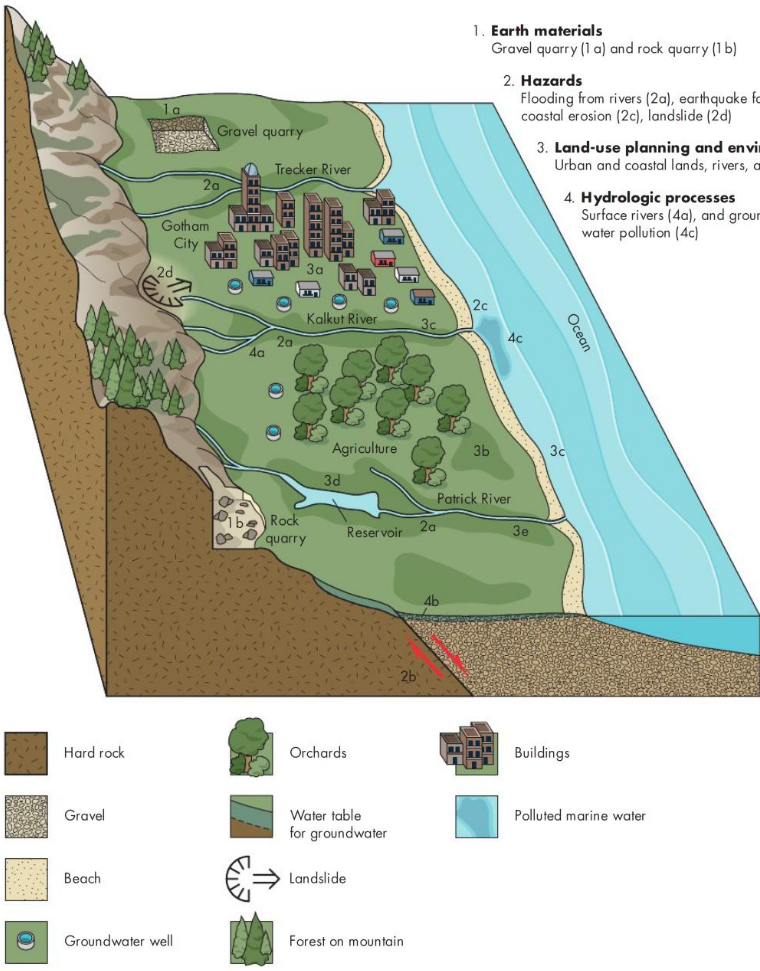


Figure 1: Components of environmental geology, Idealized diagram illustrating four main areas of study for environmental geology. Geologic processes encompass all of the four areas.

Considering the breadth of its applications, we can further define environmental geology as the branch of Earth science that studies the entire spectrum of human interactions with the physical environment. In this context, environmental geology is a branch of environmental science, the science of linkages between physical, biological, and social processes in the study of the environment.

2. Fundamental concepts of environmental geology

Before we begin to explore the many facets of environmental geology, there are some basic concepts that need to be introduced. These five fundamental concepts serve as a conceptual framework for the environmental studies.

1. Human population growth
2. Sustainability
3. Earth as a system
4. Hazardous Earth processes
5. Scientific knowledge and values

1. Concept One: Human Population Growth

The number one environmental problem is the increase in human population. For most of human history, our numbers were small, as was our input on Earth. With the advent of agriculture, sanitation, modern medicine, and, especially, inexpensive energy sources such as oil, we have proliferated to the point where our numbers are a problem. The total environmental impact from people is estimated by the impact per person times the total number of people. Therefore, as population increases, the total impact must also increase. As population increases, more resources are needed and, given our present technology, greater environmental disruption results.

What Is the Population Bomb?

Overpopulation has been a problem in some areas of the world for at least several hundred years, but it is now apparent that it is a global problem. From 1830 to 1930, the world's population doubled from 1 to 2 billion people. By 1970 it had nearly doubled again, and, by the year 2000, there were about 6 billion people on Earth. The problem is sometimes called the population bomb, because the exponential growth of the human population results in the explosive increase in the number of people (Figure 2). Exponential growth of humans means that the number of people added to the population each year is not constant; rather, a constant percentage of the current population is added each year.

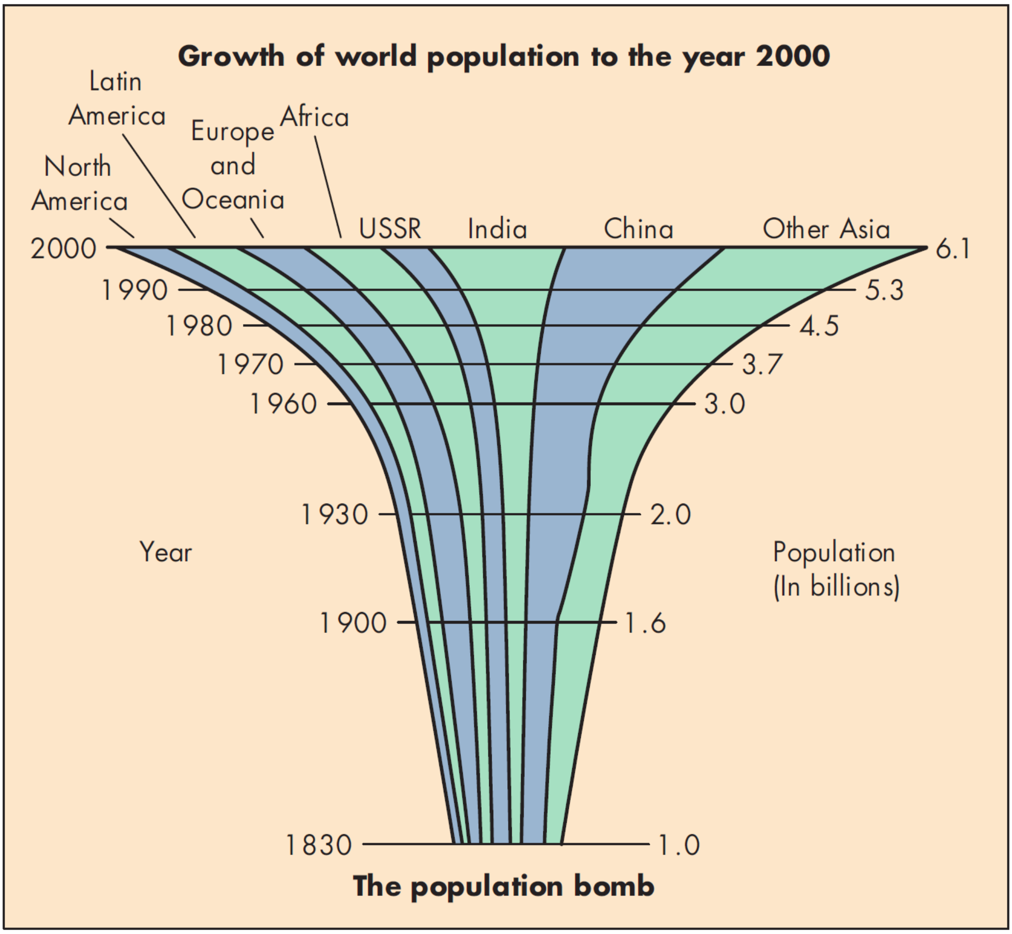


Figure 2: The population bomb. The population in 2006 is 6.6 billion and growing.

The Earth Is Our Only Suitable Habitat:

The Earth is now and for the foreseeable future the only suitable habitat we have, and its resources are limited. Some resources, such as water, are renewable, but many, such as fuels and minerals, are not. Other planets in our solar system, such as Mars, cannot currently be considered a solution to our resource and population problems. We may eventually have a colony of people on Mars, but it would be a harsh environment, with people living in bubbles. When resource and other environmental data are combined with population growth data, the conclusion is clear: It is impossible, in the long run, to support exponential population growth with a finite resource base. Therefore, one of the primary goals of environmental work is to ensure that we can defuse the population bomb. Some scientists believe that population growth will take care of itself through disease and other catastrophes, such as famine. Other scientists are optimistic that we will find better ways to control the population of the world within the limits of our available resources, space, and other environmental needs.

2. Concept Two: Sustainability

What is sustainability? Sustainability is something that we are struggling to define. One definition is that sustainability is development that ensures that future generations will have equal access to the resources that our planet offers. Sustainability also refers to types of development that are economically viable, do not harm the environment, and are socially just. Sustainability is a long-term concept, something that happens over decades or even over hundreds of years. It is important to acknowledge that sustainability, with respect to use of resources, is possible for renewable resources such as air and water. Sustainable development with respect to nonrenewable resources such as fossil fuels and minerals is possible by, first, extending their availability through conservation and recycling; and, second, rather than focusing on when a particular nonrenewable resource is depleted, focusing on how that resource is used and developing substitutes for those uses.

There is little doubt that we are using living environmental resources such as forests, fish, and wildlife faster than they can be naturally replenished. We have extracted minerals, oil, and groundwater without concern for their limits or for the need to recycle them. As a result, there are shortages of some resources. We must learn how to sustain our environmental resources so that they continue to provide benefits for people and other living things on the planet.

3. Concept Three: Earth as a System

A system is any defined part of the universe that we select for study. Examples of systems are a planet, a volcano, an ocean basin, or a river. Most systems contain several component parts that mutually adjust to function as a whole, with changes in one component bringing about changes in other components. For example, the components of our global system are water, land, atmosphere, and life. These components mutually adjust, helping to keep the entire Earth system operating.

Input-Output Analysis

Input-output analysis is an important method for analyzing change in systems. Figure 3 identifies three types of change in a pool or stock of materials; in each case, the net change depends on the relative rates of the input and output. Where the input into the system is equal to the output (a), a rough steady state is established and no net change occurs. The example shown is a university in which students enter as freshmen and graduate four years later at a constant rate. Thus, the pool of university students remains a constant size. At the global scale, our planet is a roughly steady-state system with respect to energy: Incoming solar radiation is roughly balanced by outgoing radiation from Earth. In the second type of change, the input into the system is less than the output (b). Examples include the use of resources such as fossil fuels or groundwater and the harvest of certain plants or animals. If the input is much less than the output, then the fuel or water source may be completely used up or the plants or animals may become extinct. In a system in which input exceeds output (c), the stock of whatever is being measured will increase. Examples include the buildup of heavy metals in lakes from industrial pollution or the pollution of soil and water.

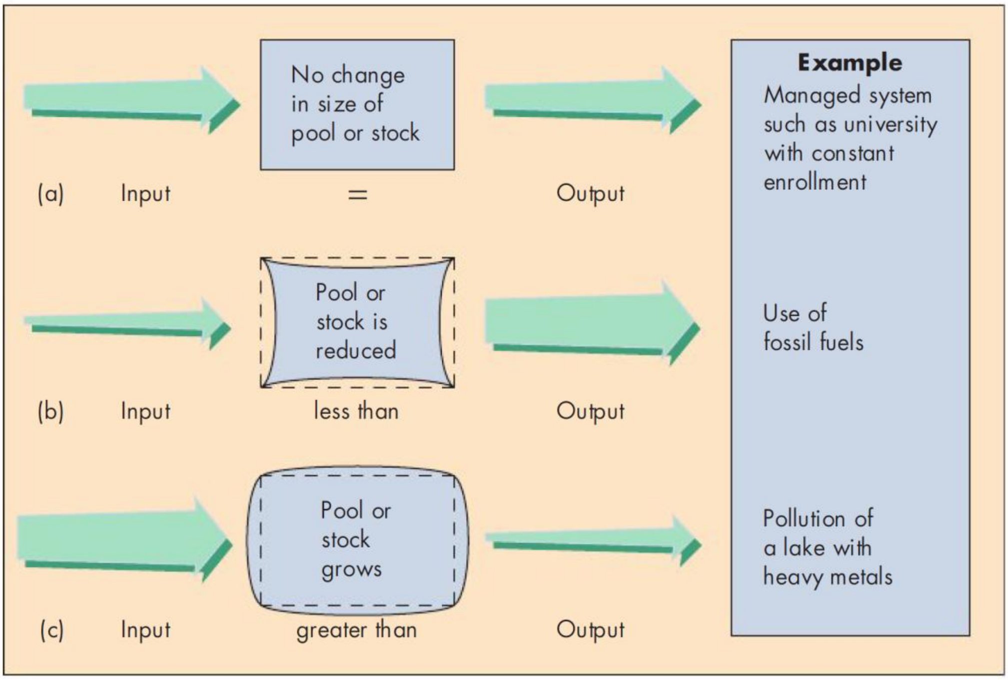


Figure 3: Change in systems Major ways in which a pool or stock of some material may change.

Environmental Unity: The principle of environmental unity, which states that one action causes others in a chain of actions, is an important principle in the prediction of changes in the Earth system. For example, if we constructed a dam on a river, a number of changes would occur. Sediment that moved down the river to the ocean before construction of the dam would be trapped in the reservoir. Consequently, beaches would be deprived of the sediment from the river, and the result of that deprivation may be increased coastal erosion. There being less sediment on the beach may also affect coastal animals such as sand crabs and clams that use the sand. Thus, building the dam would set off a chain or series of effects that would change the coastal environment and what lived there. The dam would also change the hydrology of the river and would block fish from migrating upstream. We will now consider global linkages.

Earth Systems Science: Earth systems science is the study of the entire planet as a system in terms of its components. It asks how component systems (subsystems of the Earth system), such as the atmosphere (air), hydrosphere (water), biosphere (life), and lithosphere (rocks), are linked and have formed, evolved, and been maintained. It also explores how these components function, and how they will continue to evolve over periods ranging from a decade to a century and longer. Because these systems are linked, it is also important to understand and be able to predict the impacts of a change in one component on the others.

The challenge is to learn to predict changes likely to be important to society and then to develop management strategies to minimize adverse environmental impacts. For example, the study of atmospheric chemistry suggests that our atmosphere has changed over millennia. Trace gases, such as carbon dioxide, have increased by about 100 percent since 1850. Chlorofluorocarbons (CFCs), used as refrigerants and aerosol-can propellants and released at the surface, have migrated to the stratosphere, where they react with energy from the Sun, causing destruction of the ozone layer that protects Earth from harmful ultraviolet radiation.

4. Concept four: Hazardous Earth Processes

There have always been Earth processes that are hazardous to people. These natural hazards must be recognized and avoided when possible, and their threat to human life and property must be minimized.

We humans, like all animals, have to contend with natural processes such as storms, floods, earthquakes, landslides, and volcanic eruptions that periodically damage property and kill us. During the past 20 years, natural hazards on Earth have killed several million people. The annual loss was about 150,000 people, and annual financial damages were about $20 billion.

Natural Hazards That Produce Disasters Are Becoming Superdisasters Called Catastrophes

Early in human history, our struggle with natural Earth processes was mostly a day-to-day experience. Our numbers were neither great nor concentrated, so losses from hazardous Earth processes were not significant. As people learned to produce and maintain a larger and, in most years, more abundant food supply, the population increased and became more concentrated locally. The concentration of population and resources also increased the impact that periodic earthquakes, floods, and other natural disasters had on humans. This trend has continued, so that many people today live in areas likely to be damaged by hazardous Earth processes or susceptible to the adverse impact of such processes in adjacent areas. An emerging principle concerning natural hazards is that, as a result of human activity (population increase and changing the land through agriculture, logging, mining, and urbanization), what were formerly disasters are becoming catastrophes.

We can recognize many natural processes and predict their effects by considering climatic, biological, and geologic conditions. After Earth scientists have identified potentially hazardous processes, they have the obligation to make the information available to planners and decision makers who can then consider ways of avoiding or minimizing the threat to human life or property.

5. Concept five: Scientific Knowledge and Values

Geologists are excited by the discovering something previously unknown about how the world works. These discoveries drive them to continue their work. Given that we know little about internal and external processes that form and maintain our world, how do we go about studying it? The creativity and insight that may result from scientific breakthroughs often begin with asking the right question pertinent to some problem of interest to the investigators. If little is known about the topic or process being studied, they will first try to conceptually understand what is going on by making careful observations in the field or, perhaps, in a laboratory. On the basis of his or her observations, the scientist may then develop a question or a series of questions about those observations. Next, the investigator will suggest an answer or several possible answers to the question. The possible answer is a **hypothesis** to be tested. The best hypotheses can be tested by designing an experiment that involves data collection, organization, and analysis. After collection and analysis of the data, the scientist interprets the data and draws a conclusion. The conclusion is then compared with the hypothesis, and the hypothesis may be rejected or tentatively accepted. Often, a series of questions or multiple hypotheses are developed and tested. If all hypotheses suggested to answer a particular question are rejected, then a new set of hypotheses must be developed. This method is sometimes referred to as the **scientific method**. The steps of the scientific method are shown in Figure 4. The first step of the scientific method is the formation of a question in this case, "Where does beach sand come from?" In order to explore this question, the scientist spends some time at the beach. The scientist notices some small streams that flow into the ocean; he/she knows that the streams originate in the nearby mountains. The scientist then refines the question to ask specifically, "Does beach sand come from the mountains to the beach by way of streams?" This question is the basis for the scientist's hypothesis: Beach sand originates in the mountains. To test this hypothesis, the scientist collects some sand from the beach and from the streams and some rock samples from the mountains. He/she then compares their mineral content. The scientist finds that the mineral content of all three is roughly the same. He/she draws a conclusion that the beach sand does come from the mountains, and so accepts the hypothesis. If the hypothesis had proved to be wrong, the scientist would have had to formulate a new hypothesis. In complex geologic problems, multiple hypotheses may be formulated and each tested. This is the method of multiple working hypotheses. If a hypothesis withstands the testing of a sufficient number of experiments, it may be accepted as a **theory**. A theory is a strong scientific statement that the hypothesis supporting the theory is likely to be true but has not been proved conclusively. New evidence often disproves existing hypotheses or scientific theory; absolute proof of scientific theory is not possible. Thus, much of the work of science is to develop and test hypotheses, striving to reject current hypotheses and to develop better ones.

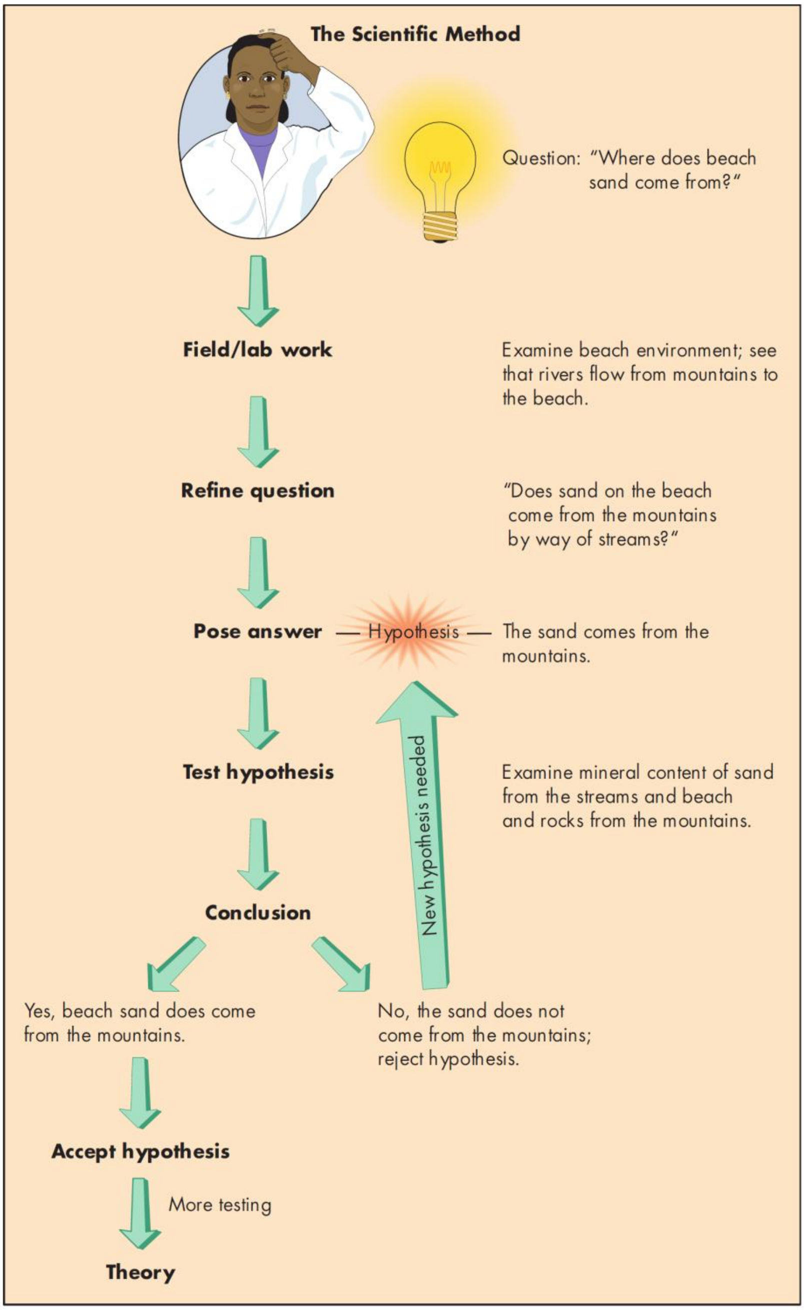


Figure 4: The steps in the scientific methods.

3. Earth Materials and Processes

Earth, our home, is a dynamic place. Over periods of hundreds to a few thousands of years (recorded history) to hundreds of thousands and millions of years, we observe change in the land and climate and study the geologic record to interpret longer term change.

3.1 The Geologic Cycle

Throughout much of the 4.6 billion years of Earth history, the materials on or near the earth's surface have been created, maintained, and destroyed by numerous physical, chemical, and biological processes. Continuously operating processes produce the earth materials land, water, and atmospheric necessary for our survival. Collectively, these processes are referred to as the geologic cycle, which is really a group of subcycles:

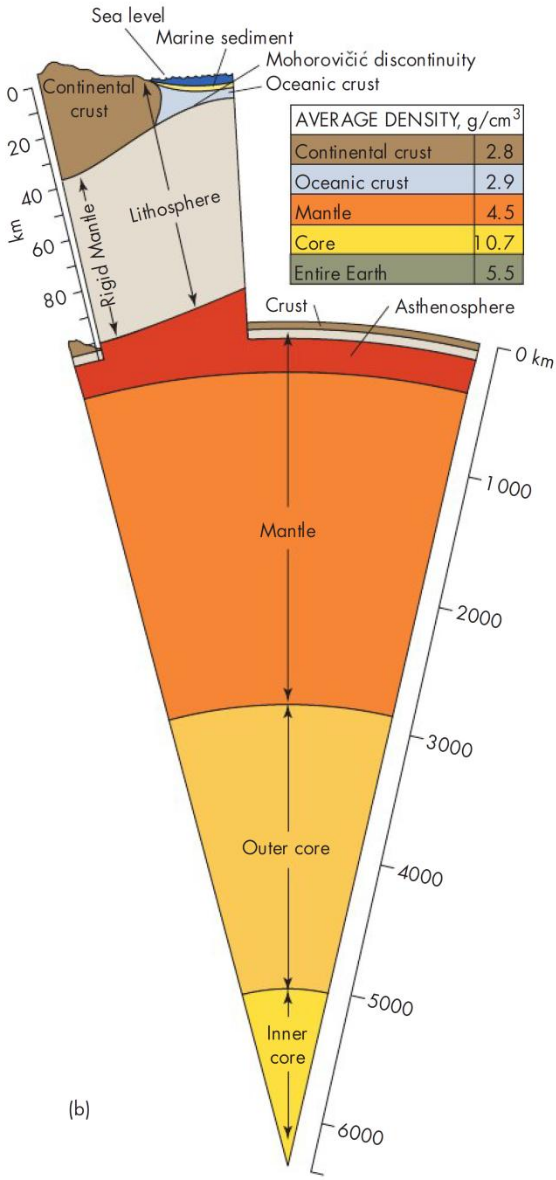
- Tectonic cycle
- Rock cycle
- Hydrologic cycle
- Biogeochemical cycles

3.1.1 The Tectonic cycle

The term tectonic refers to the large-scale geologic processes that deform the earth's crust, producing landforms such as ocean basins, continents, and mountains.

Earth s Lithosphere and Crust The outer layers of the earth are shown in Figure 5. The outermost layer, called the lithosphere, is stronger and more rigid than deeper material. Below the lithosphere lies the asthenosphere, a hot and plastically flowing layer of relatively low-strength rock that is present to a depth of about 250 km. Through detailed study of ocean basins and continents, earth scientists have established that the lithosphere averages about 100 km in thickness, ranging from a few kilometers beneath the crests of mid-ocean ridges to 120 km beneath ocean basins to 20 to 400 km beneath continents. The outer part of the lithosphere is the crust. Crustal rocks are less dense on the average than the rocks below, but oceanic crust is denser than continental crust. Oceanic crust is also thinner: The ocean floor has an average crustal thickness of about 7 km, whereas continents are about 30 km thick on the average and up to 70 km thick beneath mountainous regions.

Figure 5: Idealized diagram showing the internal structure of Earth and its layers extending from the center to the surface. Notice that the lithosphere includes the crust and part of the mantle, and the asthenosphere is located entirely within the mantle. Properties of the various layers have been estimated based on interpretation of geophysical data (primarily seismic waves from earthquakes) and examination of rocks, thought to have been brought up from below by tectonic processes.



Movement of the Lithospheric Plates Unlike the asthenosphere, which is thought to be more or less continuous, the lithosphere is broken into large pieces called lithospheric plates that move relative to one another. Processes associated with the origin, movement, and destruction of these plates are collectively known as **plate tectonics**.

A lithospheric plate may include both a continent and part of an ocean basin or an ocean basin alone. Some of the largest plates are the Pacific, North American, South American, Eurasian, African, and Australian plates, but there are many smaller plates that are significant on a regional scale. The boundaries between lithospheric plates are geologically active areas where most earthquakes and volcanic activity occur. In fact, plate boundaries are defined as the areas where most seismic activity takes place. It is at these boundaries that plates are formed and destroyed, cycling materials from the interior of the Earth to the crust and back again. Because of this continuous recycling, tectonic processes are collectively called the tectonic cycle.

Types of Plate Boundaries As a result of the cycle of plate formation, movement, and destruction, plates have the three types of boundaries (Figure 6) divergent, convergent, and transform. It is important to understand that these boundaries are not narrow cracks but zones that are tens or hundreds of kilometers across.

Divergent boundaries occur where new lithosphere is being produced and plates are moving away from each other. Typically, this occurs at mid-ocean ridges, and the process is called seafloor spreading.

Convergent boundaries occur where plates are colliding. If an oceanic plate collides with a plate carrying a continent, the higher-density oceanic plate sinks, or subducts, beneath the leading edge of the continental plate. Convergent boundaries of this type are called subduction zones. However, if the leading edges of both plates are composed of continental rocks, it is more difficult for subduction to start. In this case a continental collision boundary may develop, in which the edges of the plates crumple into mountains. This type of convergent boundary condition has produced some of the highest linear mountain systems on Earth, such as the Alpine and Himalayan mountain belts.

Transform boundaries, or transform faults, occur where the offset segments of two plates slide past one another. Most such boundaries occur in oceanic crust, but some occur on continents. A well-known continental transform boundary is the San Andreas fault in California, where a segment of the Pacific plate is sliding horizontally past a segment of the North American plate.

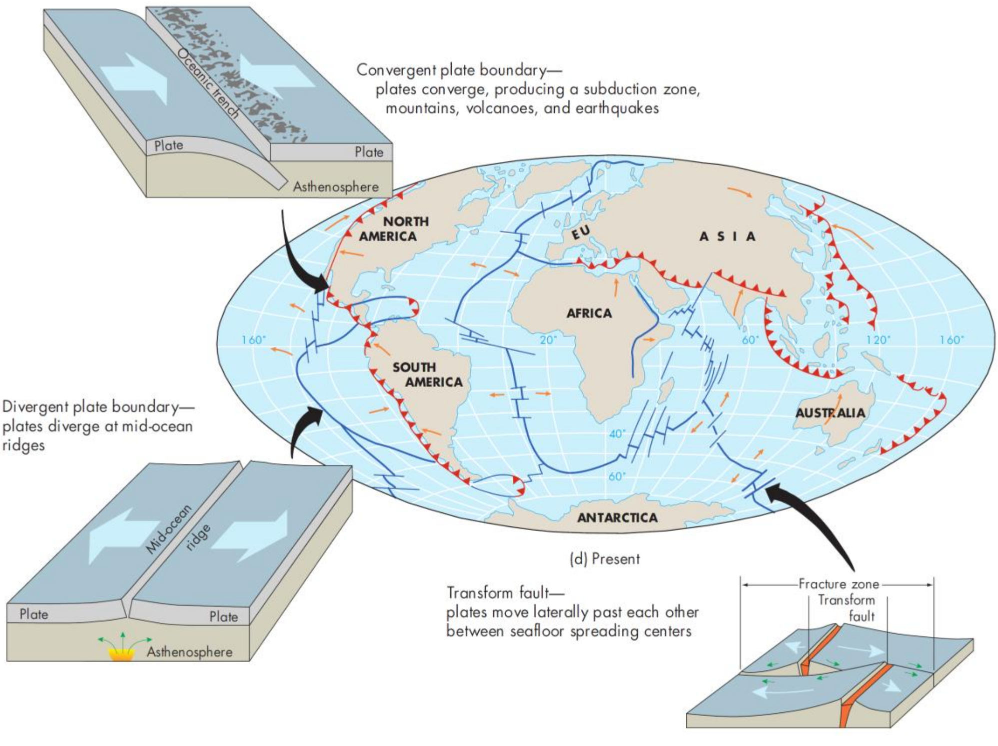


Figure 6: Plate boundaries, Arrows show directions of plate motion.

The Tectonic Cycle and Environmental Geology The importance of the tectonic cycle to environmental geology cannot be overstated. Everything living on the planet is affected by plate tectonics. As the plates slowly move a few centimeters per year, so do the continents and ocean basins, producing zones of resources (oil, gas, and minerals), as well as earthquakes and volcanoes. Tectonic processes occurring at plate boundaries largely determine the properties of the rocks and soils upon which we depend for construction and agriculture. In addition, plate motion over millions of years changes or modifies flow patterns in the oceans, influencing global climate as well as regional variation in precipitation. These changes affect the productivity of the land and its desirability as a place to live.

3.1.2 The Rock Cycle

Rocks are aggregates of one or more minerals, naturally occurring crystalline substances with defined properties. Rock cycle is the largest of the geologic subcycles. The rock cycle is linked to all the other subcycles; it depends on the tectonic cycle for heat and energy, the biogeochemical cycle for materials, and the hydrologic cycle for water, which is used in the processes of weathering, erosion, transportation, deposition, and lithification of sediments.

Although rocks vary greatly in their composition and properties, they can be classified into three general types, or families, according to how they were formed in the rock cycle (Figure 7). We may consider this cycle a worldwide rock-recycling process driven by the Earth's internal heat, which melts the rocks subducted in the tectonic cycle.

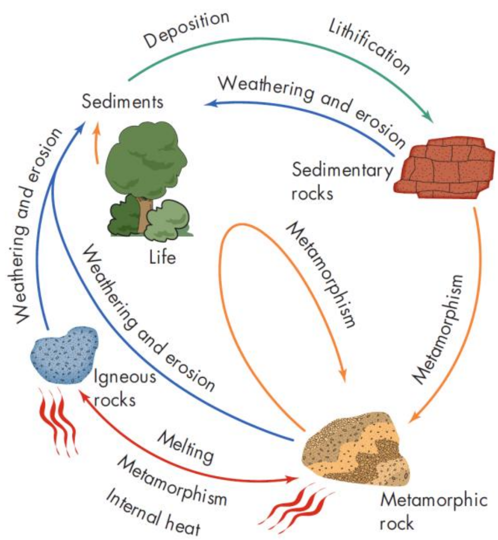


Figure 7: **The rock cycle** The rock cycle showing three rock families and processes.

Crystallization of the molten rock produces **igneous rocks** beneath and on the Earth's surface. Rocks at or near the surface break down chemically and physically by **weathering**, forming sediments that are transported by wind, water, and ice to depositional basins such as the ocean. The accumulated layers of sediment eventually undergo *lithification* (conversion to solid rock), forming **sedimentary rocks**. Deeply buried sedimentary rocks may be *metamorphosed* (altered in form) by heat, pressure, or chemically active fluids to produce **metamorphic rocks**, which may be buried still more deeply and melt, beginning the cycle again. Some variations of this idealized sequence are shown in Figure 7. For example, an igneous or metamorphic rock may be altered into a new metamorphic rock without undergoing weathering or erosion. In brief, the type of rock formed in the rock cycle depends on the rock's environment.

The Rock Cycle and Mineral Resources The rock cycle is responsible for concentrating as well as dispersing materials, a fact that is extremely important to the mining of minerals. If it were not for igneous, sedimentary, and metamorphic processes that concentrate minerals, it would be difficult to extract these resources. We take resources that have been concentrated by a rock-cycle process, transform them through industrial activities, and then return them in a diluted form to the cycle, where they are dispersed by other earth processes.

3.1.3 The Hydrologic Cycle

The **hydrologic cycle** is the movement of water from the oceans to the atmosphere and back again (Figure 8). Driven by solar energy, the cycle operates by way of evaporation, precipitation, surface runoff, and subsurface flow. Only a very small amount of the total water in the cycle is active near the earth's surface at any one time. For example, all water in the atmosphere, rivers, and shallow subsurface environment on earth is only about 0.3 percent of the total (more than 97 percent is in the oceans). Nevertheless, this small amount of nonmarine water at or near the surface of the Earth is tremendously important in facilitating the movement and sorting of chemical elements in solution, sculpturing the landscape, weathering rocks, transporting and depositing sediments, and providing our water resources.

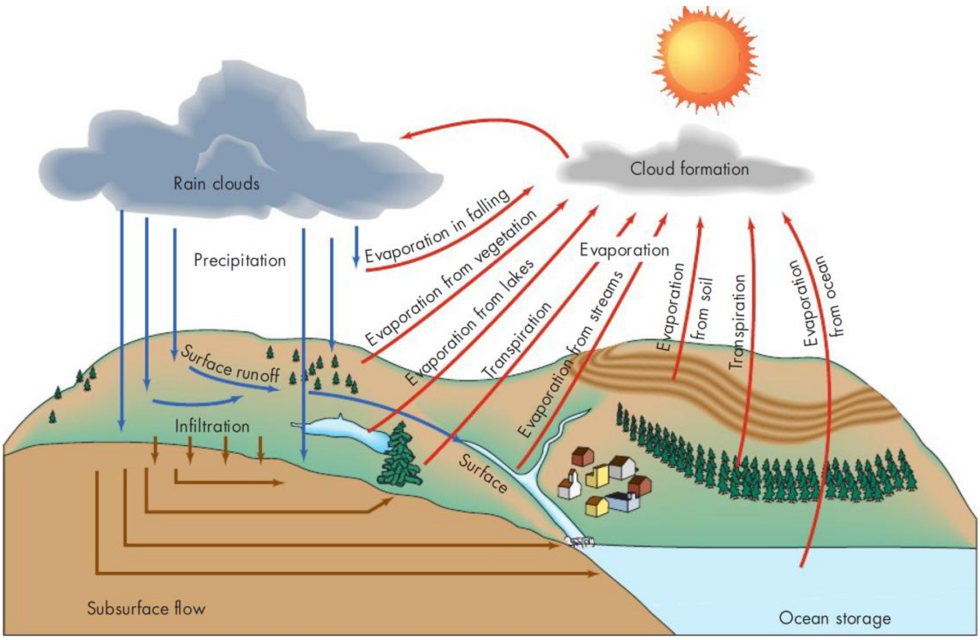


Figure 8: **Hydrologic cycle** Idealized diagram showing the hydrologic cycle illustrating important processes and transfer of water.

3.1.4 Biogeochemical Cycles

A **biogeochemical cycle** is the transfer or cycling of an element or elements through the atmosphere (the layer of gases surrounding the earth), lithosphere (earth's rocky outer layer), hydrosphere (oceans, lakes, rivers, and groundwater), and biosphere (the part of the earth where life exists). It follows from this definition that biogeochemical cycles are intimately related to the tectonic, rock, and hydrologic cycles. The tectonic cycle provides water from volcanic processes, as well as the heat and energy required to form and change the earth materials transferred in biogeochemical cycles. The rock and hydrologic cycles are involved in many transfer and storage processes of chemical elements in water, soil, and rock.

Biogeochemical cycles can most easily be described as the transfer of chemical elements through a series of storage compartments or reservoirs (e.g., air, soil, groundwater, vegetation). When a biogeochemical cycle is well understood, the rates of transfer, or flux, between all of the compartments is known. However, determining these rates on a global basis is a very difficult task. The amounts of such important elements as carbon, nitrogen, and phosphorus in each compartment and their rates of transfer between compartments are only approximately known.

To better understand biogeochemical cycles, we will discuss the global carbon cycle, diagrammed in Figure 9. Carbon in its pure form is found in some minerals such as graphite and diamonds and in recently discovered exotic molecules composed of 60 carbon atoms each and known as "buckyballs". More important to us, however, are the many compounds carbon forms with other elements. Carbon is the basic building block of life because it readily combines with other carbon atoms and with oxygen and hydrogen to form biological compounds. As a result, the carbon biogeochemical cycle is intimately related to the cycles of oxygen and hydrogen. Some carbon compounds are gases under ordinary conditions. The most important of these gases is carbon dioxide (CO_2), which is found in the atmosphere, soil, and other parts of the environment.

Figure 9 shows the amount of carbon in the various storage compartments, as well as rates of transfer between compartments on an annual basis. The cycling of carbon between the atmosphere, oceans, and life is a relatively quick process. Over very long periods of geologic time, the carbon in the atmosphere is modulated by the carbonate-silicate cycle. Carbon dioxide in the atmosphere dissolves in water to form weak carbonic acid (H_2CO_3) that falls as rain. As the weak acid moves through soil and rock, it weathers the abundant silica rich rock, releasing a variety of weathered products including calcium ions (Ca^{2+}) and bicarbonate ions (HCO_3^-). When transported to the ocean by surface and groundwater, calcium and bicarbonate are used by small floating marine organisms (plankton) to build their calcium carbonate shells. When they die and their shells sink to the bottom, they become sediment. The sediment accumulates and is carried by moving plates of oceanic crust to subduction zones. With increased temperature, pressure, and partial melting of subducted crust, the magma that feeds volcanoes is produced. The CO_2 is released back into the atmosphere with the volcanic eruptions.

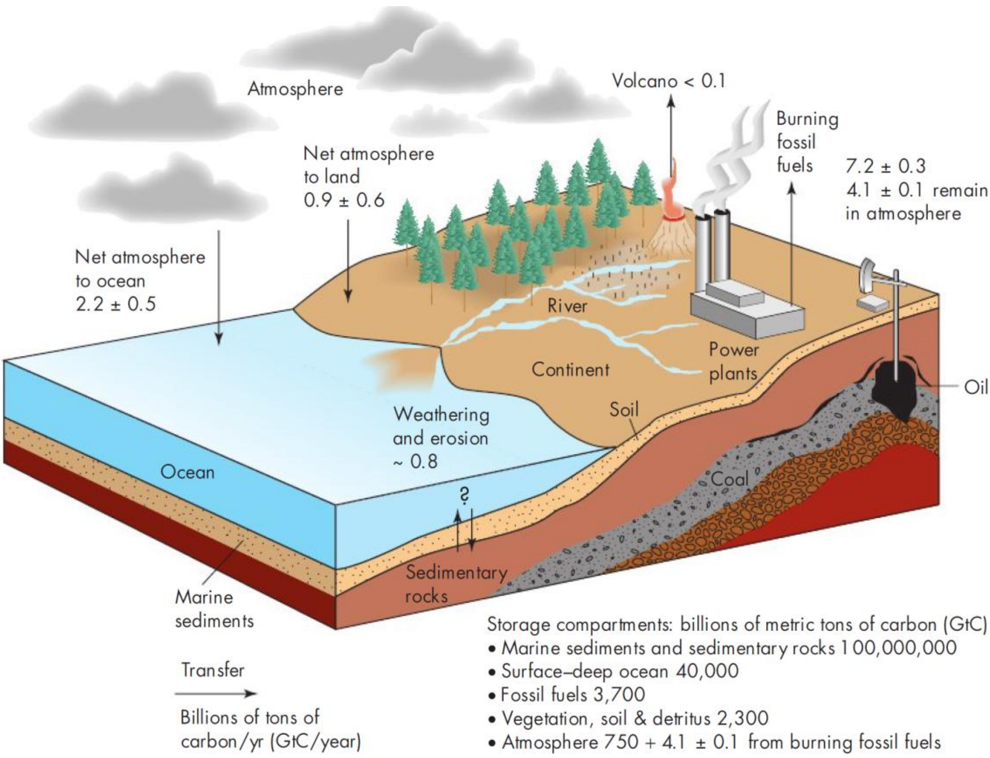


Figure 9: Simplified carbon cycle.

As the carbon dioxide concentration in the atmosphere increases because of natural change or the burning of fossil fuels, the global climate also changes. Notice in Figure 9 that about 7.2 $\pm$ 0.3 billion metric tons of carbon per yr (GtC/yr) are added to the atmosphere from the burning of fossil fuels, but the annual increase of carbon to the atmosphere is 4.1 $\pm$ 0.1 GtC. The difference between 7.2 GtC/yr and 4.1 GtC/yr is 3.1 GtC/yr. This is the net rate that carbon is transferred from the atmosphere to the ocean (2.2 GtC/yr) plus the net rate that carbon is transferred from the atmosphere to the land (0.9 GtC/yr).

2 Earthquakes

2.1 Earthquake magnitude

Almost all earthquakes, and certainly all major earthquakes, are related to the slow but steady motion of the earth's plates.

Plate boundaries are locked

Although the plates are constantly in motion (at rates of a few cm per year, or approximately 0.1 mm per day) the rocks present at the places where plates meet (eg. at convergent boundaries and transform faults) are not necessarily sliding past each other. In most cases, particularly within a few tens of kilometres of surface, the friction between rocks at a boundary is great enough so that the two plates will be locked together. As the plates themselves gradually move, the rocks close to the boundary are elastically deformed. According the **elastic rebound theory**, energy is being stored in the rocks as they are deformed. Eventually the strain will become so great that the friction that is preventing movement between the plates will be overcome. The plates will suddenly slide past each other, and the stored energy will be released, producing an earthquake [Keller: Figure 7.18].

Energy released as body waves

A huge amount of energy radiates away from the focus of the earthquake in the form of deformation waves in the rock. These include **P-waves** (primary or compression waves) and **S-waves** (secondary or shear waves) - both of which propagate within the rock and are also known as **body waves.** When the body waves reach surface some of their energy will be transferred into surface waves, including **Love waves** (horizontal motion) and **Rayleigh waves** (vertical motion), which propagate along the interface between the rock and the surface [Keller: Figure 7.8].

Surface waves

Stress transfer

Once the first displacement takes place along the earthquake fault much of the stress which had been built up will be released, and much of the rock in the area will return back to an unstressed state. On the other hand, it has been shown recently that while an earthquake will release stress in some areas, it is likely to add to the stress in other areas. In the seconds, minutes, hours, days, weeks, years and even decades following the initial earthquake some of that added stress will be released in the form of aftershocks, both along the same fault plane, and along other fault planes in the region. (see below under *Stress transfer and aftershocks*)

Where earthquakes happen

A majority of the world's earthquakes take place along the transform faults associated with spreading ridges, but most of these are small because the rocks in these areas are relatively warm, and almost all are insignificant because they occur well away from populated areas. Some large earthquakes (> M 7) occur along larger transform boundaries - such as the San Andreas and Queen Charlotte Faults, the Anatolian Fault in Turkey or the Alpine Fault in New Zealand - however most very large earthquakes (> M 8) are generated at convergent boundaries within subduction zones.

Factors affecting the degree of locking

The severity of earthquakes generated in any area will depend partly on the degree to which the two plates are locked together in different parts of the fault zone. The degree of locking will depend on several factors, including the rock types, the level of water saturation along the boundary, and, most importantly, the temperature.

Rock type

- The rock type is important for two reasons. The presence of weak or poorly consolidated rocks will prevent a fault zone from becoming locked - or at least it will reduce the extent of the locking. The presence of certain minerals, particularly clays or graphite, will lubricate a fault zone and also reduce the locking tendency.

Water

- Water will lubricate a fault zone, and thus will reduce the tendency for locking to take place.

Temperature

- Temperature, which increases systematically with depth, can affect the tendency for locking. As the temperature increases beyond 450º C most rocks begin to behave plastically and the locking tendency is reduced dramatically.

Focus and epicentre

The actual location of an earthquake within the earth, is called its "focus" (a.k.a. hypocenter) [Keller: Figure 7.8]. The point on the surface directly above the focus is known as the "epicentre". The location of an earthquake is determined from seismic records, specifically by measuring the time interval between the first P wave and the first S wave [Keller: Figure 7.16]. By comparing distances from several seismic stations it is possible to determine the location of the epicentre. If enough accurate data are available it is also possible to determine the depth, or the location of the focus. Most earthquakes occur within the range of 5 to 100 km depth, and all very strong earthquakes originate within this range. The maximum depth for earthquakes is 700 km because at greater depths the rocks are too hot and plastic to behave in a brittle manner.

Magnitude

Earthquake magnitude - which is an indication of the amount of energy released by an earthquake - is expressed on a number of different scales, all of which provide slightly different types of information. Some of the methods for calculating magnitudes are summarized on the table below.

Richter magnitude

The first widely applied magnitude scale was the **Richter Scale** (after the American seismologist Charles F. Richter). Richter magnitude (M_L) (the L refers to *local* because this technique is only applicable for quakes within a few hundred km of the seismic station) is determined from the maximum amplitude of the S waves recorded on a **Wood-Anderson** seismograph, and is corrected for the distance between the epicentre and the seismic station. There are very few operating Wood-Anderson seismographs today, but seismologists have adapted the algorithm so that comparable results can be obtained from other seismometers.

Magnitude type	Applicable magnitude range	Applicable distance range	Comments
Local or Richter (M_L)	2 to 6	0-400 km	The original magnitude relationship defined in 1935 by Richter and Gutenberg for Californian earthquakes. It is based on the maximum amplitude of S waves recorded on a Wood-Anderson torsion seismograph. Although these instruments are no longer widely in use, M_L values can be calculated using data from modern instruments.
Moment (M_W)	> 3.5	All	Based on the **seismic moment** of the earthquake, which is equal to the strength of the rock times the average amount of slip on the fault times the fault area that slipped.
Surface wave (M_S)	5 to 8	20 to 180°	A magnitude for distant earthquakes based on the amplitude of Rayleigh surface waves measured at a period near 20 sec.
Body (M_B)	4 to 7	16 to 100° (only deep quakes)	Based on the amplitude of P body-waves. This scale is most appropriate for deep-focus earthquakes.
Duration (M_D)	<4	0-400 km	Based on the duration of shaking as measured by the time decay of the amplitude of the seismogram. Commonly used to compute magnitude from seismograms with "clipped" waveforms due to limited dynamic recording range of analog instrumentation.
Tsunami (M_T)	large		Only applicable to large subduction-zone earthquakes which produce under-sea displacement. Based on wave height.

Partly derived from the USGS glossary of terms for earthquakes.

Summary of methods used for calculation of earthquake magnitude

(Partly derived from the USGS glossary of terms for earthquakes)

Moment magnitude

Moment magnitude is an expression of the energy released by an earthquake based on the size (area) of the rupture surface, the average displacement or slip distance, and the strength of the rock that broke. Of these values, the area of the rupture surface is the most variable[1], and hence the most significant to the final result. In fact, because the strength of the rocks being broken doesn't vary all that much, seismologists normally substitute a constant for this variable, a value of $3x10^{11}$ dyne/cm^2. The first part of the calculation of moment magnitude involves estimation of what is known as the **seismic moment**, as follows:

$$M_O = GLWu$$

where G is the rock strength value ($3x10^{11}$ dyne/cm^2), L and W are the length and width of the fault rupture surface (in cm), and u is the average amount of displacement (in cm)[2]. Using some typical values, it is easy to see that seismic moments are very big numbers. For example, consider an earthquake for which the rupture surface is **10 km long** and **2 km wide** (ie. *deep* for a vertical fault), and if the average displacement is **50 cm**, the seismic moment value is as follows:

$$M_O = (3 \text{ x } 10^{11} \text{ dyne/cm}^2) \text{ x } (\mathbf{10 \text{ x } 10^5 \text{ cm}}) \text{ x } (\mathbf{2 \text{ x } 10^5 \text{ cm}}) \text{ x } (\mathbf{50 \text{ cm}}) = 3.0 \text{ x } 10^{24} \text{ dyne}\cdot\text{cm}$$

The moment magnitude is derived from the seismic moment using the following equation:

$$M_W = 2/3 \text{ x } (\log_{10}(M_O)) - 10.73$$

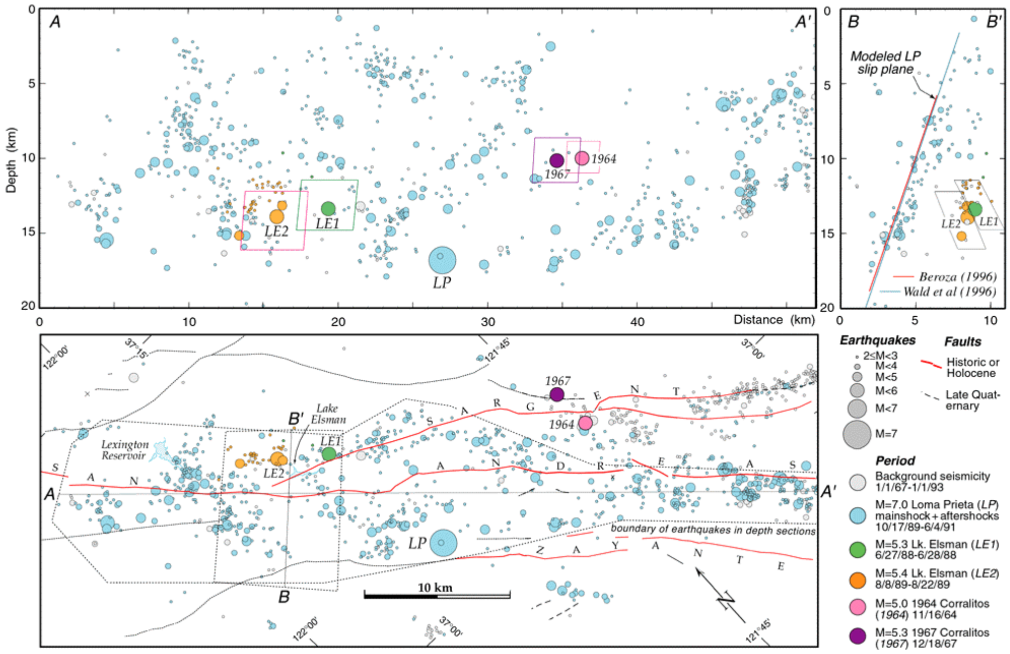
For the earthquake described above the moment magnitude is **5.59**.

Rupture zone

Seismologists acquire the information needed for moment magnitude calculations from seismic records for the main shock and the immediate aftershocks of an earthquake. In the case of a large earthquake there may be thousands of aftershocks, and these would be distributed around the area of the rupture surface. By carefully plotting the locations all of the events it is possible to estimate the length and width of the rupture zone. An example of the extent of the rupture surface for the 1989 Loma Prieta earthquake is shown on Figure 2.1. The length of the fault plane defined by the blue dots is around 50 km and the width (depth) is close to 20 km. The displacement was around 2 m and hence M_W=7.12.

[1] The length of a rupture zone may vary from a few tens metres to hundreds of kilometres, and the width from a few metres to over 100 kilometres. The displacement distance may vary from centimetres to tens of metres

[2] The amount of slip will vary quite widely in different parts of the rupture surface. It will be greatest near to the centre of the surface, and least near to the edges.



Distribution of shocks (blue circles) which define the rupture surface of the 1989 Loma Prieta ("World Series") earthquake

(The upper-left panel is a section along the fault, the upper right panel is a cross-section, the lower panel is a plan view.)

Estimation of displacement

If the rupture plane of the earthquake reached surface, and the displacement can be measured, this information can be used to help estimate the average slip distance. Other information, such as the amounts of subsidence and uplift in different places can also be used to help with this estimate. In many cases there is no surface manifestation of the earthquake, and the amount of slip can only be guessed, or estimated from other information, such as the rate of plate motion and the time interval since the last earthquake.

Moment magnitude is a much more accurate and relevant way of expressing earthquake energy than Richter magnitude - especially for large earthquakes - and it is being used increasingly by seismologists. When an earthquake occurs the Richter magnitude can be calculated within minutes or hours, and this is the number that is quickly released to the press, and hence is the number that sticks in people's minds. It can take days or even weeks to assemble enough data to calculate the moment magnitude.

Other magnitude estimations

Some other ways of expressing earthquake energy, as summarized in the table above, are as follows:

Surface-wave magnitude (Ms): based on the amplitude of surface waves and the distance to the epicentre (only applicable to earthquakes at least 20 (approx. 1600 km) away from the seismic station)[3].

[3] Surface-wave magnitude can also be used to estimate moment magnitude where the parameters of the rupture surface are not known.

Tsunami magnitude (Mt): based on the size of tsunami waves recorded at various locations (applicable only to subduction-zone earthquakes where there is underwater vertical displacement).

Earthquke incidence

Each year there are about 20 earthquakes over magnitude 7, and more than 100 over magnitude 6. Earthquakes over magnitude 8 are much less frequent, and those over 9 are typically decades apart. An earthquake over magnitude 3 can only be felt in the area immediately around the epicentre, and there are tens of thousands of these each year. The largest earthquakes occur along subduction zones in areas of converging plates in places like Chile, Ecuador, Alaska, Japan and Indonesia. Earthquakes over magnitude 8.5 have been measured in all of these areas.

Magnitude scales are logarithmic

All magnitude scales are logarithmic. A difference of 1 unit is equivalent a 10-fold difference in the amplitude of the waves on a seismograph, but to a 32-fold difference in the amount of energy released. The recent (Dec. 2004) M9 earthquake in Indonesia released the equivalent amount of energy as 32 M8 earthquakes and over 1000 M7 earthquakes. In other words, this earthquake released as much energy as all other earthquakes combined over approximately the past decade.

2.2 Earthquake intensity, harmonic amplification and liquefaction

Earthquake intensity

Earthquake intensity, or the amount of damage likely to be caused by an earthquake, is measured on the Mercalli Scale, [Keller: Table 7.2] which was developed in the late 1800's, and later modified by Giuseppe Mercalli. The scale ranges from I to XII, and values are assigned based on interviews with witnesses and assessment of damage to structures. The intensity assigned to the area immediately around the epicentre is normally much higher than that assigned to areas tens or hundreds of kilometres away. Events with intensities up to around III won't even be noticed by most people. Where the intensity is around VI there will be minor damage to buildings. If the intensity is X or more many buildings will be destroyed, and there will be serious damage to dams and bridges and triggering of landslides.

Regional variations in intensity

Variations in intensity with respect to distance from the epicentre will be affected by regional geology. In Eastern North America, for example, where the underlying rocks are generally old, hard and strong, the effects of an earthquake are felt over a much wider area than in western North America, where the rocks are generally younger, softer, weaker and more variable. Variations in Mercalli intensity around the 1994 Northridge (California) earthquake are shown on Keller's Figure 7.17.

Damage

In fact the amount of damage caused by an earthquake will normally be more

3 Volcanism

3.1 Characteristics of magmas

In order to understand the processes of volcanism it is essential to be aware of the nature of the magmas that produce volcanic eruptions. These magmas are derived from two main sources, as follows:

Magma derived from the mantle

> **The mantle -** This includes the lower mantle for mantle-plume (hot-spot) volcanoes, such as those on the Hawaiian Islands; and the upper mantle for rift-related volcanism, including the oceanic ridges, and areas such as the Rift Valley of East Africa. Both types of mantle-derived magma are strongly mafic and generally poor in water and other volatiles (see table below). Mantle-plume and rift-related magmas are not exactly the same. The upper mantle is compositionally different from the lower mantle, and the conditions of magma formation are different. In both cases the process of magma formation is by partial melting of mantle material. In the upper mantle that is largely a result of decreased pressure in rift areas. We don't fully understand how magmas are formed in the lower mantle, but it has a lot to do with the heat of the underlying core.

Magma derived from subduction zones

> **Melting at subduction zones -** The subducting slab includes lithosphere, oceanic crust and some sea-floor sediment. Compared with the surrounding mantle this material is rich in water - both as free water, and as water in hydrated minerals such as clays. This water plays a critical role in lowering the melting point of both the subducting material and the mantle. The resulting melt products rise up to the base of the crust. Some of this material may continue to rise up through the crust, but it is likely that most of the magma generated in this environment is a result of partial melting of the lower crust by the heat of the magma generated on the subduction zone. Magmas in the crust are almost certainly affected by the surrounding crustal rocks. Most magma chambers that supply subduction zone volcanoes have overall intermediate compositions, but various processes that take place near to surface can lead to wide variability in the composition of erupting material. These magmas are relatively rich in volatiles, including water (see table below).

Magma compositions

All magmas are composed predominantly of eight elements, including oxygen, silicon, aluminum, iron, calcium, magnesium, sodium and potassium. Magmas also contain volatile constituents, such as hydrogen, carbon, sulphur, chlorine and nitrogen. Excluding oxygen, the major components of most crustal rocks are positively charged, and in view of the abundance of oxygen, the cations are almost always complexed with oxygen. Geologists commonly express the compositions of igneous rocks in terms of the weight percentages of the oxides, and typical values for the oxides and volatile components in felsic, intermediate and mafic rocks (and magmas) are listed in the table below.

Magma melting temperatures

Apart from the important differences in silica content, there are substantial differences in the contents of iron, calcium, magnesium, potassium and volatiles. The chemical differences are associated with significant differences in melting temperatures - which are around 1200º C for mafic magmas, as opposed to less than 1000º C for felsic magmas. These temperatures are highly dependant on water contents, and are significantly lower for wet magmas.

Another very important difference is the viscosity of the different types of magma. Mafic magmas are generally very runny (a little like ketchup), while felsic magmas are much more viscous (a little like peanut butter). (see figure below) The differences in viscosity are largely related to the silica contents and the tendency for silica tetrahedra to polymerize (form together into chains) even before any minerals begin to crystallize from the magma. Mafic magmas also tend to be hotter than felsic magmas, and this contributes to their low viscosity.

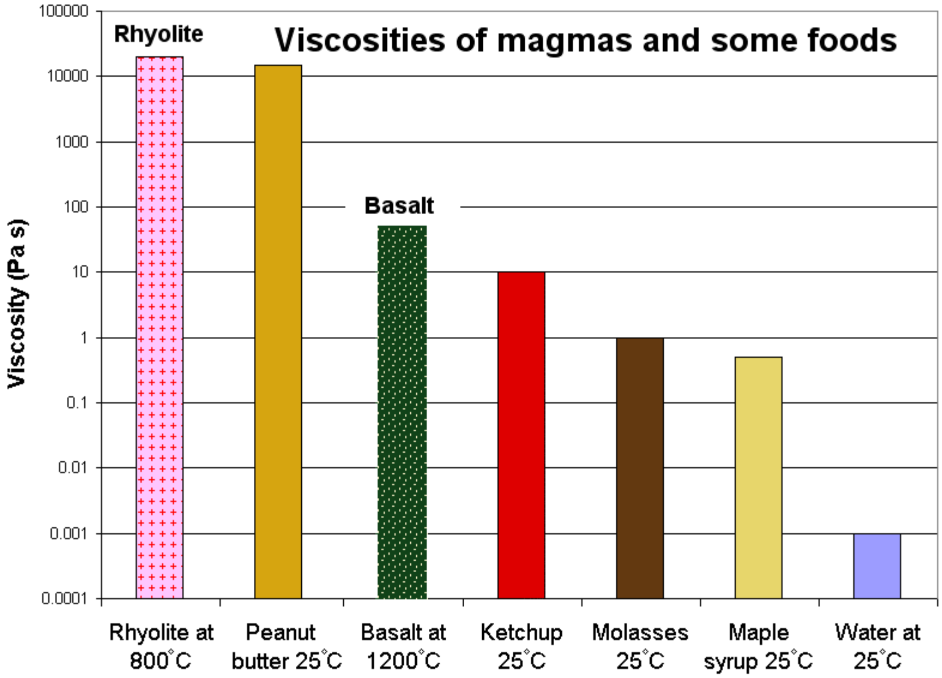
Generalized chemical compositions of felsic, intermediate and mafic magmas

Oxide	**Felsic magma (granite/rhyolite)**	**Intermediate magma**	**Mafic magma (gabbro/basalt)**
SiO_2	65-75%	55-65%	45-55%
Al_2O_3 *	14.0%	16.5%	15.5%
Fe_2O_3	1.5%	2.5%	3.3%
FeO**	1.4%	6.4%	8.1%
CaO	1.7%	6.0%	9.5%
MgO	0.6%	3.0%	7.3%
Na_2O	3.7%	3.6%	2.7%
K_2O	4.2%	2.4%	1.0%
Volatiles	4-6%	3-4%	1-2%

* Ranges are given for SiO_2 only, but the levels of the other oxides are also variable
** Fe_2O_3 represents oxidized (Fe^{3+}) iron, while FeO represents reduced (Fe^{2+}) iron.
(adapted from Best, 1982)

Magma eruption styles

Different magma types erupt in different ways. Eruptions of mafic magmas are normally quite gentle and controlled because the magma flows easily, the volatile content is quite low and the gases that are present can quickly escape through the liquid without causing an explosion. In contrast, eruptions of intermediate, and particularly felsic magmas, can be highly explosive because the magma does not flow easily and gets stuck in conduits, the volatile levels are high and the gases cannot escape easily through the thick magma.



(after Baker et al., 2004)

Magma viscosities

As any magma approaches the surface the pressure drops. Within a few hundred metres of surface the gases start to exsolve (come out of solution), and the gas volume increases dramatically. At the same time a lot of tiny crystals (microlites) start to form. The exsolution of gases and formation of microlites both make the magma even more viscous than it was before. As the magma moves even closer to surface the gas bubbles increase in size and number, and this causes the overall volume of the magma to increase dramatically. In the case of a felsic magma most of the gas is unable to migrate towards the surface (because the magma is too viscous), and thus when the gas expands it caused the magma to expand as well. This expansion puts huge pressures on the conduit and the volcanic dome, and eventually something gives way leading to an eruption. In mafic magmas, (that have relatively low gas contents in the first place), much of the gas is able to migrate to surface and as it expands it only affects the magma close to the surface.

Formation of gas bubbles and microlites in magmas

The magmas at volcanoes related to hot-spots and oceanic ridges are derived from the mantle and, in most cases, they move only through mantle material (or oceanic crust) on their way to the surface. Their initial compositions are consistently mafic, and there is little opportunity for modification of the composition through contact with other rocks. The volcanic eruptions in places like Hawaii and Iceland are generally consistent in style, and usually relatively peaceful, although there are some exceptions, as described below.

Magma at hot spots

In contrast, the magmas at subduction zones are derived from material of varying compositions. They are mostly made up of mantle rock that melts when water from the subducting plate migrates into the mantle, but they may also include some component of oceanic plate and the relatively wet sediments on its upper surface. As they ascend to the base of the crust and then up through the crust these magmas come into contact with various different rock types and they assimilate material from these rocks. That assimilation occurs in two different ways, firstly as a result of the melting

Magma at subduction zones

of the country rock adjacent to the magma chamber, and secondly as fragments of country-rock break away and mix with the magma - a process known as **stoping**. Another important aspect of subduction-zone magmas is that they are stored in magma chambers at depths of several kilometers below surface. This allows for ongoing interaction with the surrounding rock, and for differentiation within the magma body.

Varying compositions of subduction magmas

The consequence of the assimilation of crustal material and of storage within magma chambers is that the magmas feeding subduction-zone volcanoes can have widely varying compositions, and hence the volcanic eruptions, even at one location, can be very different in style. These magmas are almost always considerably more felsic than the magmas at hot spots and spreading ridges.

Gases in magmas

Numerous gases are released during the eruption of magmas, but the most common is water - which comprises over 90% of the total. Others, in general order of importance, are carbon dioxide (CO_2), sulphur dioxide (SO_2), hydrogen sulphide (H_2S), carbon monoxide (CO), nitrogen (N_2), hydrogen (H_2), hydrochloric acid (HCl) and methane (CH_4). These gases (and liquid water at surface temperatures) contribute to the oceans and the atmosphere, and they also comprise the main elements of life (carbon, hydrogen, oxygen and nitrogen).

3.2 Eruption types and processes

The various terms that are used to describe volcanic eruptions and events are summarized below. Many of these terms come from Italy, where volcanoes were first described in detail - beginning almost 2000 years ago[1].

Plinian eruptions

Plinian eruption
Plinian eruptions are large explosive events that send enormous dark columns of tephra and gas high into the stratosphere (many kilometres). Such eruptions are named for *Pliny the Younger*, who carefully described the disastrous eruption of Vesuvius in 79 A.D. This eruption generated a huge column of tephra into the sky, it also produced pyroclastic flows and surges, and extensive ash fall. Many thousands of people evacuated areas around the volcano, but about 2,000 were killed, including *Pliny the Older* (uncle to the younger). The massive eruption column of Mt. St. Helens in 1980 (following the lateral blast) was a plinian eruption.

The younger Pliny's comments on the Vesuvius eruption are recorded in two letters written to the historian Tacitus. These letters are available on the internet if you are interested: (http://www.mala.bc.ca/~earles/pliny)

Vulcanian eruptions

Vulcanian eruption
Vulcanian eruptions are highly explosive and relatively short-lived. The name is derived from the 1888-90 eruptions of Vulcano, a small volcano in the Eolian Islands north of Sicily. Vulcanian eruptions produce black, ash- and steam-laden columns, and they eject lava fragments that do not take on a rounded shape during their flight

[1] Much of the material on types of volcanic eruptions comes from the USGS volcano photo-glossary. http://volcanoes.usgs.gov/Products/Pglossary/pglossary.html|

through the air. This may be because the lava is too viscous or because it is already solidified. These moderate-sized explosive eruptions commonly eject a large proportion of volcanic ash and also bread-crust bombs and blocks. Andesitic and dacitic magmas are most often associated with vulcanian eruptions, because their high viscosity makes it difficult for the dissolved volcanic gases to escape except under extreme pressure, which leads to explosive behavior. The explosive eruptions at Montserrat in 1997 were primarily vulcanian in character.

Strombolian eruption

Strombolian eruptions

Strombolian eruptions (named for the Stromboli volcano in Italy) are characterized by the intermittent explosion or fountaining of basaltic lava from a single vent or crater. Each episode is caused by the release of volcanic gases, and they typically occur every few minutes or so, sometimes rhythmically and sometimes irregularly. The lava fragments generally consist of partially molten volcanic bombs that become rounded as they fly through the air.

Effusive eruption

Effusive eruptions

An eruption dominated by the non-explosive outpouring of lava onto the ground is often referred to as an effusive eruption. Most, but not all effusive eruptions involve relatively non-viscous magmas. Lava flows generated by effusive eruptions vary in shape, thickness, length, and width depending on the type of lava erupted, the rate of discharge, the slope of the ground over which the lava travels, and the duration of the eruption.

For example, basaltic lava may form textures such as *aa* or *pahoehoe*, and flow in deep narrow channels or in thin wide sheets. Andesitic lava typically forms thick stubby flows, and dacitic lava often forms steep-sided mounds called lava domes.

Most of the Hawaiian and Icelandic eruptions are effusive in nature.

Phreatic eruption

Phreatic eruptions

Phreatic eruptions are steam-driven explosions that occur when water beneath the ground or on the surface is heated by magma, lava, hot rocks, or new volcanic deposits (for example, tephra and pyroclastic-flow deposits). The intense heat of such material (as high as 1200° C for basaltic lava) may cause water to boil and flash to steam, thereby generating an explosion of steam, water, ash, blocks, and bombs. (Most of the recent (2004) eruptions at Mt. St. Helens were phreatic.)

Small phreatic explosions can occur when pyroclastic deposits flow over a small pond or area of wet ground. The heat causes the water to boil and then explode.

Pyroclastic density current

Pyroclastic density currents

A pyroclastic density current (or nuée ardente) is a ground-hugging avalanche of hot ash, pumice, rock fragments, and volcanic gas that rushes down the side of a volcano at rates as fast as several hundred km/hour. The temperature may be greater than 500° C, sufficient to burn and carbonize wood. Once deposited, the ash, pumice, and rock fragments may deform (flatten) and weld together because of the intense heat and the weight of the overlying material.

Two types of pyroclastic density currents are as follows (after Druitt, 1998):

A **pyroclastic surge** is a dilute and relatively wet suspension of material that flows in a turbulent manner, commonly at a high rate (150 m/s). In most cases they result from the gravitational collapse of an eruption column, or from a phreatic explosion, but they can also result from sudden explosions - such as the *lateral blast* of Mt. St. Helens. The deposits tend to be stratified, and they mantle the landscape rather than filling hollows.

Pyroclastic surges

A **pyroclastic flow** is more dense and poorly sorted and is normally dryer than a pyroclastic surge. The velocities are generally lower (~50 m/s). They commonly result from the destruction of lava domes, but can also be a product the gravitational collapse of an eruption column. Pyroclastic flow deposits tend not to be stratified, and they do fill hollows. They are generally more voluminous and cover wider areas than pyroclastic surge deposits.

Pyroclastic flows

Lahar

Lahars

Lahar is an Indonesian word for a rapidly flowing mixture of rock debris and water that originates on the slopes of a volcano. Lahars are also referred to as volcanic mudflows or debris flows. They form in a variety of ways, chiefly by the rapid melting of snow and ice by pyroclastic flows, intense rainfall on loose volcanic rock deposits, breakout of a lake dammed by volcanic deposits, and as a consequence of debris avalanches.

As described below, lahars are particularly dangerous because they can extend for many tens of kilometres away from the source of the eruption, and because they follow the paths of streams and rivers – places where people live.

Sector collapse

Sector collapse

The catastrophic failure of a major part of a volcano is known as sector collapse. During the 1980 eruption the side of Mt. St. Helens collapsed in the largest landslide event in history – the so-called debris avalanche. The main plinian eruption followed the collapse. That debris avalanche (see description below) was the first observed sector collapse of a volcano. Deposits like those of the debris avalanche at Mt. St. Helens have since been observed at many other volcanoes, and it is now assumed that similar events have taken place elsewhere. As the moving debris rushes down a volcano and into valleys, it incorporates water, snow, trees, bridges, buildings, and anything else in the way. Debris avalanches may travel several kilometers before coming to rest, or they may transform into more water-rich lahars, which travel many tens of kilometers downstream.

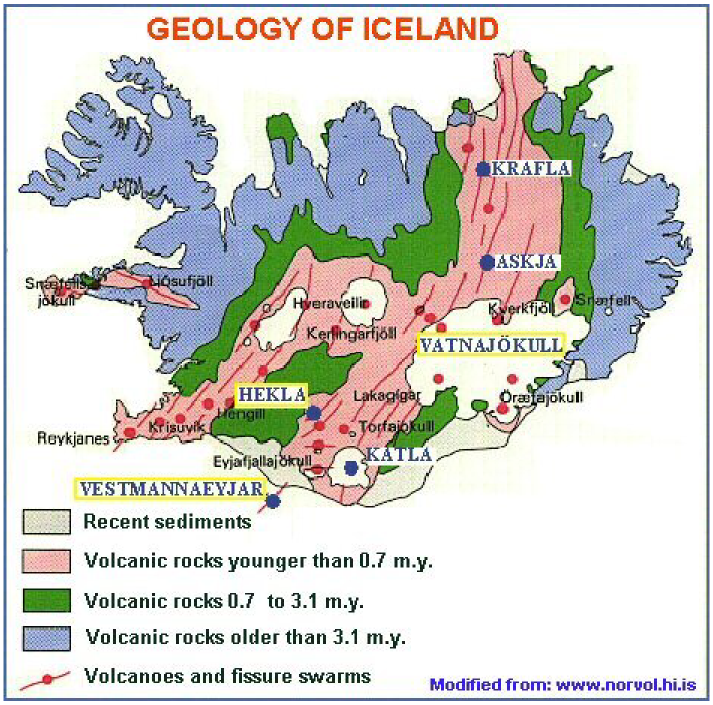
A good part of the lahar associated with the 1980 eruption at Mt. St. Helens flowed out of the bottom of the debris avalanche as it came to rest and lost much of its water.

3.3 Volcanism in Iceland

Iceland is geologically unique in that it represents an exposure of an oceanic spreading ridge. Spreading ridges are normally underwater of course, but Iceland rises above the level of the Atlantic Ocean because it is also the site of a major mantle plume and the underlying mantle is hot and buoyant[2].

Geological map of iceland

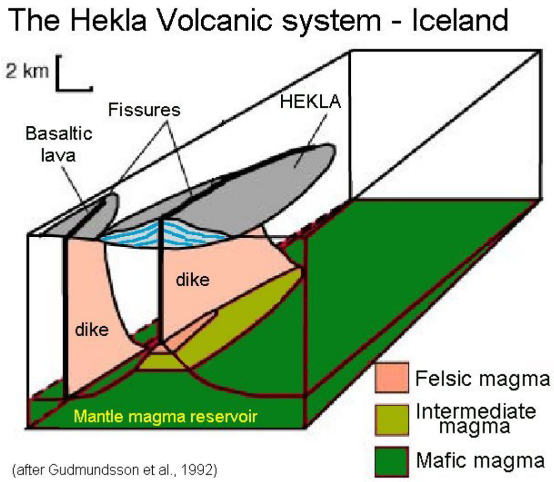
Most of Iceland is basaltic in composition and is younger than 4 m.y. (see figure). The oldest rocks are at the western and eastern extremities. Most of the recent volcanic activity has been confined to a strip between 50 and 100 km wide, in the east-central part of the island, on either side of the spreading ridge. The rocks in this area are all younger than 700,000 y. A characteristic feature of volcanism on Iceland is the eruption of lava from long fissures opened up by the tensional forces of the mid-Atlantic spreading system. Some of these fracture systems are shown on the figure above.



1873 eruption at Lika

During 1873 a 25 km long fissure opened up near to Lika (close to Lakagigar at the edge of the main ice cap), and lava poured out a rate of up to 5000 cubic metres per second for 50 days. This is the most voluminous lava flow in recorded history. To put it into perspective, the rate of flow of lava was greater than the average flow of water in the Fraser River. When the eruption ended an area of 565 square kilometres was covered in lava, to an average depth of 23 m (equivalent in height to a 7-story building). The eruption was characterized by a very high discharge of sulphur dioxide (SO_2), which spread out across Europe in a blue haze of sulphuric acid droplets (sulphate aerosols), causing an unusually cold winter. A large amount of fluorine was also released, and this accumulated on vegetation, resulting in the death of more than half of the island's horses and cattle. The ensuing famine took 10,000 lives, some 20% of the Icelandic people.

[2] A great deal of information on Icelandic volcanism can be found at http://www.norvol.hi.is

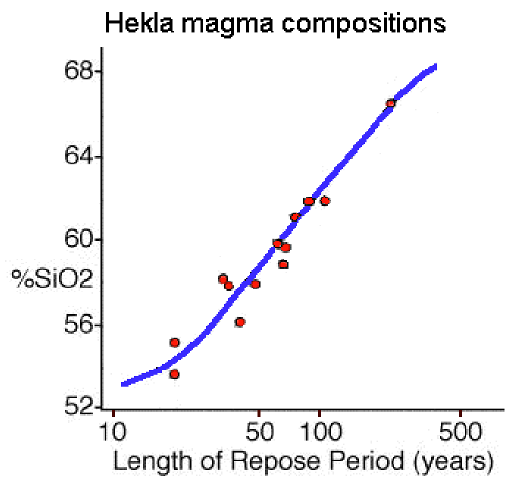


(after Gudmundsson et al., 1992)

Hekla volcano

3-dimensional view of the Hekla volcanic system

While most of Iceland's volcanism is strongly mafic (basaltic) in composition, and the resulting lavas normally spread out across the terrain rather than forming mountains, there are a few volcanoes (ie. volcanic mountains). The most famous (and active) of these is Hekla, a 1500 m peak situated in the south-central part of the country. The magma that formed Hekla is unique for Iceland in having an overall andesitic composition. This is similar to that of the average for a subduction-zone volcano; and like the subduction volcanoes, Hekla is a composite cone - comprised of material with differing compositions (see figure). The magma of Mt. Hekla is not derived directly from the mantle, but passes through a magma chamber that is situated at a depth of approximately 8 km. Considering that crust beneath Iceland is essentially oceanic in character (and therefore quite thin), this means that the chamber is close to or at the interface between the crust and the mantle.



(after Gudmundsson et al., 1992)

Silica composition of Hekla magma as a function of the repose time between eruptions

Studies of magma composition have shown that the longer the time lapse between eruptions, the more felsic the resulting magma at Hekla will be, and the more violent the eruption. The relationship between the magma composition (SiO_2) and the gap time between eruptions is given on the figure to the right. It has been inferred from this that during long periods of non-activity the magma chamber tends to become well zoned and the magma at the top is particularly felsic. It is suggested that a number of different processes taking place with the magma chamber lead to this phenomenon. There may be simple density stratification (settling of the more mafic components to the bottom of the chamber) Crystal settling may also be a factor, if olivine and pyroxene crystallize out in the cooler upper parts of the chamber, and then settle towards the bottom. It is also likely that there is partial melting of some of the surrounding rocks. It could be this partial melting that give the magma its overall andesitic composition, because there is little doubt that the material feeding into the magma chamber - from the mantle - is strongly mafic. The term *partial melting* is the key, because the hot magma will tend to preferentially melt the felsic component of the existing crustal rocks with which it is in contact, and thus the overall composition of the magma in the magma chamber will become more felsic.

Eruptions at Mt. Hekla normally produce large volumes of **tephra** (ash and other larger solid particles, a.k.a. **pyroclastic** deposits) that cover a significant part of the country. Following the initial explosive eruption, there are usually many months of relatively quiet flows of more mafic (andesitic or basaltic) lava. Like the Lika fissure eruption, eruptions from Hekla commonly result in the emission of large quantities of fluorine.

There was a significant eruption at Hekla in February and March of 2000. The eruption and its volcanic products are described at http://www.norvol.hi.is/

1973 Heimaey eruption

In January of 1973 there was a volcanic eruption on the tiny island of Heimaey, just off the southern cost of Iceland [Keller - page 217]. This event made the international news because the eruption occurred at the edge of the town of Vestmannaeyjar, which is situated on Iceland's most important fishing harbour. The lava flows destroyed 417 houses, and most of the other buildings were covered with a thick layer of tephra. The lava flow then continued down towards the sea, where it looked as if it might block the entrance to the harbour, and thus destroy the island's economy. In order to save the rest of their houses, and their harbour, the citizens started bulldozing piles of tephra to divert the lava flows. They also poured millions of litres of cold sea-water onto the flow front. This cooled and hardened the flow sufficiently to divert it. The harbour was saved, and in fact it is now even larger and better protected than before.

After the eruption ceased the towns-people started pumping water into the 100 m thick pile of slowly cooling lava. The water is recovered lower down, where, at a temperature of over 90º C, it is used to heat buildings. There is a lot of information on the Vestmannaeyjar eruption at: http://www.norvol.hi.is/

Over the centuries Icelanders have learned to live with volcanism, and as they did on Heimaey, they profit from it. Iceland has one of the oldest and most highly developed geothermal industries in the world. The energy from the earth is used to heat buildings, greenhouses, and swimming pools, and also to generate electricity.

3.4 Volcanism at Mt. St. Helens

Mount St. Helens

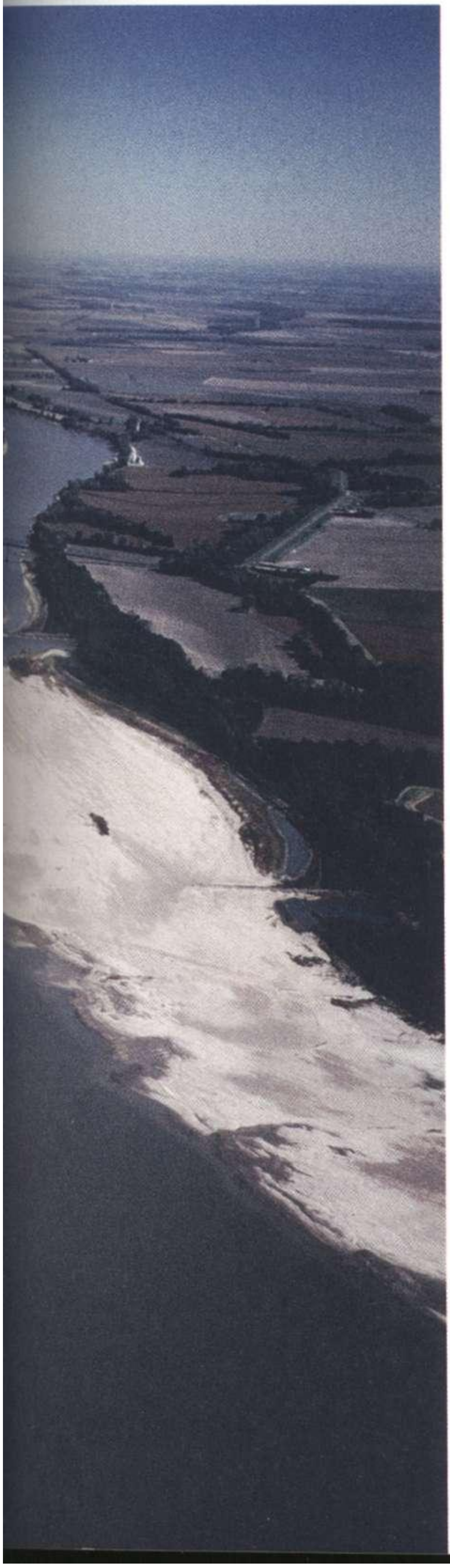
Mt. St. Helens, in southern Washington State, is one of a chain of volcanic mountains that are related to the subduction of the Juan de Fuca plate beneath the North American plate. It is a classic composite volcano, made up of lava flows and tephra that have a range of compositions[3].

Older volcanic rocks of the MSH area

All of the rocks of the area around Mt. St. Helens (MSH) are relatively young in geological terms, and the mountain itself is extremely young. The oldest rocks of the area are parts of the Siletz and Crescent Terranes, oceanic crustal rocks that were accreted onto this part of North America soon after their formation some 50 million years ago. At this time there was subduction of the oceanic plate to the west of the MSH area, and there were subduction-related volcanoes well to the west, in eastern Washington and Idaho. There was extensive sedimentation in what is now western Washington, including the formation of coal deposits.

[3] A comprehensive review of Mt. St. Helens geology, along with hundreds of photographs, is given in: **The 1980 eruption of Mt. St. Helens**, P. Lipman and D. Mullineaux (eds), *U.S. Geological Survey Prof. Paper 1250*. There are also numerous papers of interest in *Geoscience Canada*, V. 17., edited by C. Hickson and D. Peterson.

Rivers and Flooding



Learning Objectives

Water covers about 70 percent of Earth's surface and is critical to supporting life on the planet. However, water can also cause a significant hazard to human life and property in certain situations, such as a flood. Flooding is the most universally experienced natural hazard. Flooding in the United States is the most common and costly natural hazard we face. Floodwaters have killed more than 10,000 people in the United States since 1900, and property damage from flooding exceeds $5 billion a year. Flooding is a natural process that will remain a major hazard as long as people choose to live and work in flood-prone areas. In this chapter we focus on the following learning objectives:

- Understand basic river processes
- Understand the nature and extent of the flood hazard
- Understand the effects of urbanization on flooding in small drainage basins
- Know the major adjustments to flooding and which are environmentally preferable
- Know the potential adverse environmental effects of channelization and the benefits of channel restoration

Confluence of the Mississippi and Ohio Rivers
(Alex S. MacLean/Peter Arnold, Inc.)

CASE HISTORY Mississippi River Flooding, 1973 and 1993

In 1973, spring flooding of the Mississippi River caused the evacuation of tens of thousands of people as thousands of square kilometers of farmland were inundated throughout the Mississippi River Valley. Fortunately, there were few deaths, but the flooding resulted in approximately $1.2 billion in property damage.[1] The 1973 floods occurred despite a tremendous investment in upstream flood-control dams on the Missouri River. Reservoirs behind these dams inundated some of the most valuable farmland in the Dakotas, and despite these structures, the flood near St. Louis was record breaking.[2] Impressive as this flood was at the time, it did not compare either in magnitude or in the suffering it caused with the flooding that occurred 20 years later.

During the summer of 1993 the Mississippi River and its tributaries experienced one of the largest floods of the century. There was more water than during the 1973 flood, and the recurrence interval exceeded 100 years. The floods lasted from late June to early August and caused 50 deaths and more than $10 billion in property damages. In all, about 55,000 km^2 (21,236 mi^2), including numerous towns and farmlands, were inundated with water.[3,4]

The 1993 floods resulted from a major climatic anomaly that covered the upper Midwest and north-central Great Plains, precisely the area that drains into the Mississippi and lower Missouri River systems.[5] The trouble began with a wet autumn and a heavy spring snowmelt that saturated the ground in the upper Mississippi River basin. Then, early in June, a high-pressure center became stationary on the East Coast, drawing moist, unstable air into the upper Mississippi River drainage basin. This condition kept storm systems in the Midwest from moving east. At the same time, air moving in over the Rocky Mountains initiated unusually heavy rainstorms.[5] The summer of 1993 was the wettest on record for Illinois, Iowa, and Minnesota. For example, Cedar Rapids, Iowa, received about 90 cm (35 in.) of rain from April through July—the equivalent of a normal year's rainfall in just 4 months![4] Intense precipitation falling on saturated ground led to a tremendous amount of runoff and unusually large floods during the summer. The floodwaters were high for a prolonged time, putting pressure on the flood defenses of the Mississippi River, particularly **levees,** which are earth embankments constructed parallel to the river to contain floodwaters and reduce flooding (Figure 8.1). Levees are constructed on the flat land adjacent to the river known as the floodplain.

Before construction of the levees, the Mississippi's floodplain, flat land adjacent to the river that periodically floods, was much wider and contained extensive wetlands. Since the first levees were built in 1718, approximately 60 percent of the wetland in Wisconsin, Illinois, Iowa, Missouri, and Minnesota—all hard hit by the flooding in 1993—have been lost. In some locations, such as St. Louis, Missouri, levees give way to floodwalls designed to protect the city against high-magnitude floods. Examination of Figure 8.2, a satellite image from mid-July 1993, shows that the river is narrow at St. Louis, where it is contained by the floodwalls, and broad upstream near Alton, where extensive flooding occurred. The floodwalls produce a bottleneck because water must pass through a narrow channel between the walls; the floodwaters get backed up waiting to get through. These

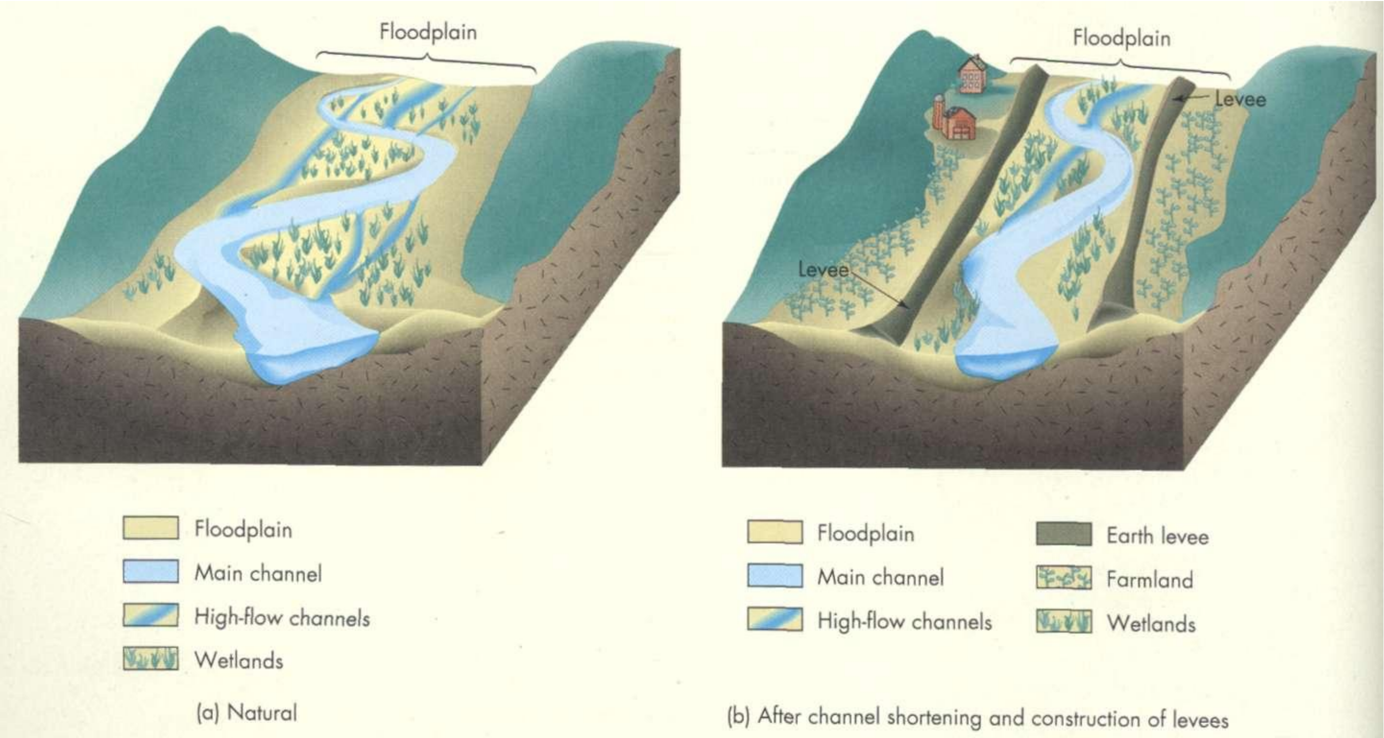


Figure 8.1 Floodplain with and without levees Idealized diagram of (a) natural floodplain (flat land adjacent to the river produced by the river) with wetlands, (b) Floodplain after channel is shortened and levees are constructed. Land behind levees is farmed, and wetlands are generally confined between the levees.

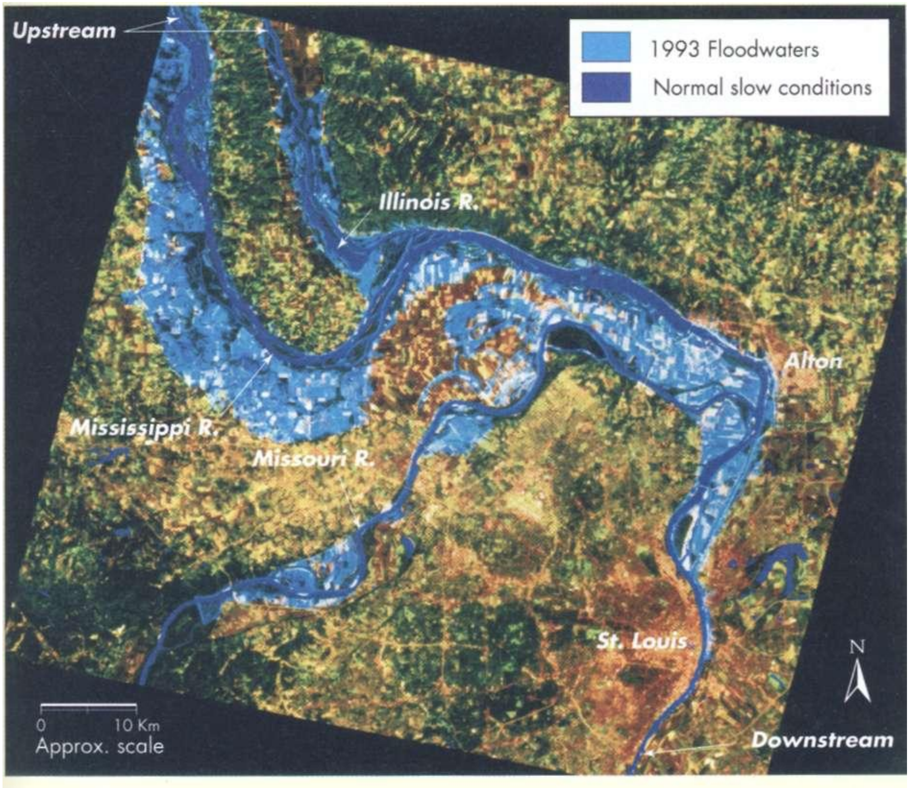


Figure 8.2 Mississippi River flood of 1993 This image shows the extent of flooding from the 1993 Mississippi River floods. In the lower right-hand corner the river becomes narrow where it flows by the city of St. Louis, Missouri (orange area in lower right corner). The river is narrow-here because flow is constricted by a series of floodwalls constructed to protect the city. Notice the extensive flooding upstream of St. Louis, Missouri. The city with its floodworks is a real bottleneck to the flow of water. The town of Alton, Illinois, is the first orange area upstream from St. Louis. This city has a notorious history of flooding. *(ITD-SRSC/RSI/SPOT Image, copyright ESA/CNES/Sygma)*

floodwaters contributed to the 1993 flooding upstream of St. Louis (Figure 8.2).

Despite the high walls constructed to prevent flooding, the rising flood peak came to within about 0.6 m (2 ft) of overtopping the floodwalls at St. Louis. Failure of levees downstream from St. Louis partially relieved the pressure, possibly saving the city from flooding. Levee failures (Figure 8.3) were very common during the flood event.[4,5] In fact, almost 80 percent of the private levees, that is, levees built by farmers and homeowners, along the Mississippi River and its tributaries failed.[4] However, most of the levees built by the federal government survived the flooding and undoubtedly saved lives and property. Unfortunately, there is no uniform building code for the levees, so some areas have levees that are higher or lower than others. Failures occurred as a result of overtopping and breaching, or rupturing, resulting in massive flooding of farmlands and towns (Figure 8.4).[4]

One of the lessons learned from the 1993 floods is that construction of levees provides a false sense of security. It is difficult to design levees to withstand extremely high-magnitude floods for a long period of time. Furthermore, the loss of wetlands allows for less floodplain space to "soak up" the floodwaters.[6] The 1993 floods caused extensive damage and loss of property; in 1995, floodwaters of the Mississippi River system inundated floodplain communities once again. Several communities along the river are rethinking strategies concerning the flood hazard and are moving to higher ground! Of course, this is exactly the adjustment that is appropriate.

Although flooding may be caused by several processes including coastal flooding from a hurricane, in this chapter we will focus on river flooding. We will discuss flooding from several perspectives, including river processes; effects of land-use changes on flooding; effects of flooding; and how flooding may be minimized.

Figure 8.3 Levee failure Failure of this levee in Illinois during the 1993 floods of the Mississippi River caused flooding in the town of Valmeyer. *(Comstock Images)*

Figure 8.4 Damaged farmland Damage to farmlands during the peak of the 1993 flood of the Mississippi River. *(Comstock Images)*

Rivers: Historical Use

For more than 200 years, Americans have lived and worked on floodplains, enticed to do so by the rich *alluvial* (stream-deposited) soil, abundant water supply, ease of waste disposal, and proximity to the commerce that has developed along the rivers. Of course, building houses, industry, public buildings, and farms on a floodplain invites disaster, but too many floodplain residents have refused to recognize the natural floodway of the river for what it is: part of the natural river system. **The floodplain,** the flat surface adjacent to the river channel that is dically inundated by floodwater, is in fact produced by the process of flooding (Figures 8.1a, 8.5, and 8.6). If the floodplain and its relation to the river are not recognized, flood control and drainage of wetlands, including floodplains, become prime concerns. It's not an oversimplification to say that as the pioneers moved they had a rather set procedure for modifying the land: First clear the landby cutting and burning the trees, then modify the natural drainage. From that history came two parallel trends: an accelerating program to control floods, matched, by an even greater growth of flood damages. In this chapter, we will consider flooding as a natural aspect of river processes and examine the successes and failures of traditional methods of flood control. We will also discuss river restoration attempts that work with the natural river processes rather than against them.

Streams and Rivers

Streams and rivers are part of the water, or hydrologic, cycle, and *hydrology* is the study of this cycle. The hydrologic cycle involves the transport of water by evaporation from Earth's surface, primarily from the oceans, to the atmosphere and, via surface and subsurface runoff from the land, back again to the oceans. Some of the water that falls on the land as rain or snow infiltrates soils and rocks; some evaporates; and the rest drains, or runs off, following a course determined by the local topography. This runoff finds its way to streams, which may merge to form a larger stream or a *river*. Streams and rivers differ only in size; that is, streams are

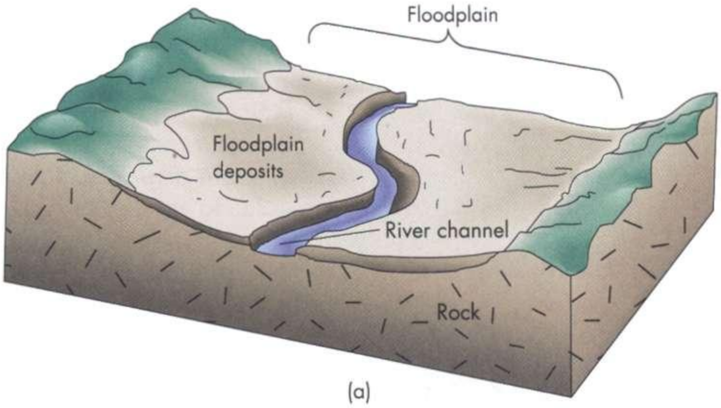
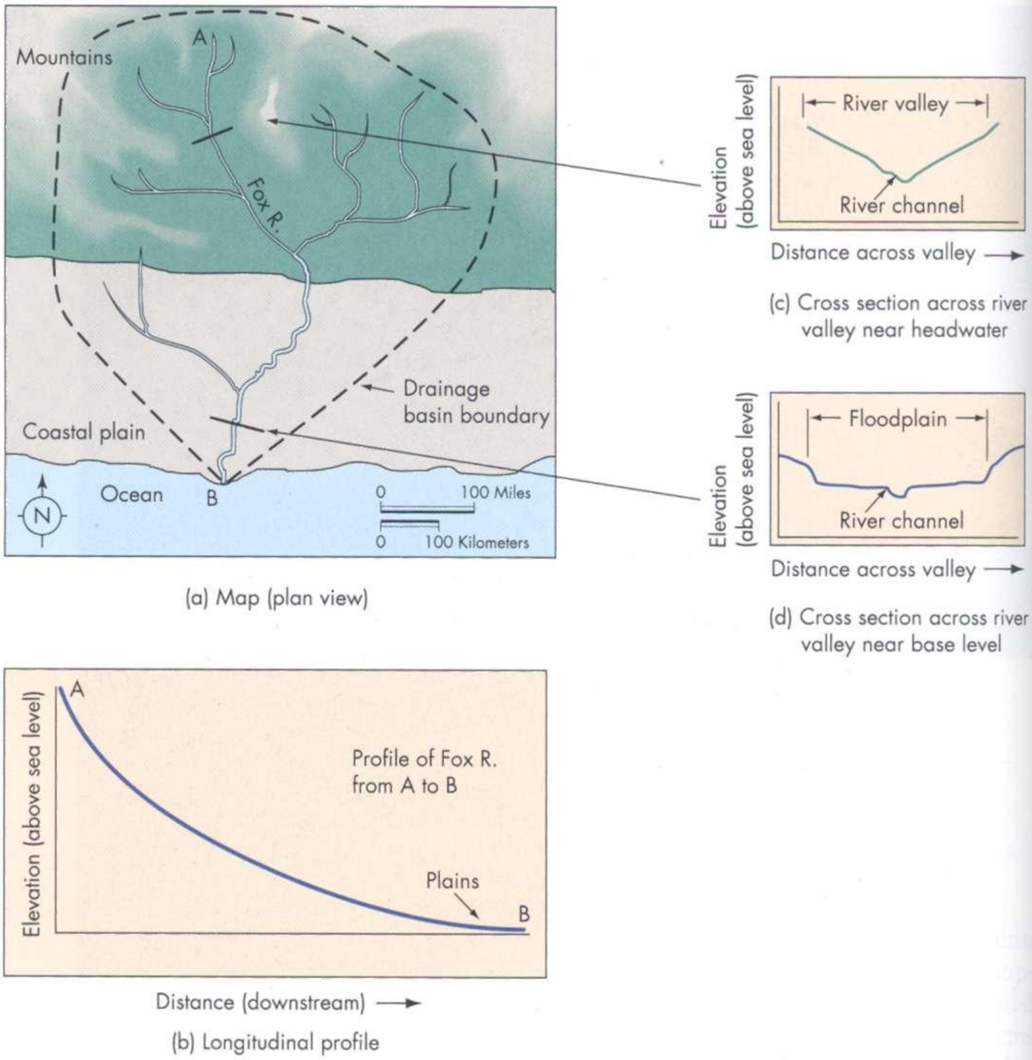


Figure 8.5 Floodplain
(a) Diagram illustrating the location of a river's floodplain. (b) Floodplain of the Rio Grande in Colorado.
(Edward A. Keller)

Figure 8.6 Floodplain inundation from snowmelt Gaylor Creek, Yosemite National Park, during spring snowmelt. (a) In the morning water is within the channel, (b) In the afternoon, during daily peak snowmelt, flow covers the floodplain. *(Edward A. Keller)*

Figure 8.7 Drainage basin and river profile Idealized diagram showing (a) drainage basin, (b) longitudinal profile of the Fox River, (c) cross section of valley near headwater, and (d) cross section near base level.



small rivers. However, geologists commonly use the term *stream* for any body of water that flows in a channel. The region drained by a single river or river system is called a drainage basin, or *watershed* (Figure 8.7a).

A river's slope, or gradient, is the vertical drop of the channel over some horizontal distance.. In g of a stream is the theoretical lowest level to which a river" may erode. Most often, the base level is at sea level, although a river may have a temporary base level such as a lake. Rivers flow downhill to their base level, and a graph of elevation of a river against distance downstream is called the longitudinal profile (Figure 8.7b). A river usually has a steeper-sided and deeper valley at high elevations near its headwaters than closer to its base level, where a wide floodplain may be present (Figure 8.7c, d). At higher elevations, the steeper slope of the river causes deeper erosion of the valley. Increased erosion is due to the higher flow velocity of the river water produced by the steeper channel slopes.

8.3 Sediment in Rivers

The total quantity of sediment carried in a river, called its *total load*, includes the bed load, the suspended load, and the dissolved load. The *bed load* moves by the bouncing, rolling, or skipping of particles along the bottom of the channel. The bed load of most rivers, usually composed of sand and gravel, is a relatively small component, generally accounting for less than 10 percent of the total load. The *suspended load,* composed mainly_of silt and clay, is carried abovethe strearribedj2y_ theflovvingjvater. The_susperuigd4oad^ccounteJQi^**r4early**90perc^**rTt**?5rtTie total load. and_makgs rivers look muddy. Thejfeso/pgc? *load* is carriedin chemical solution and is derived from chemical weathering of rocks in the drainage basin. The dissolved^oaclniay make stream water taste salty if it cohtains~large amounts of sodium and chloride. It may also make the stream water "hard" if the dissolved load contains high concentrations of calcium and magnesium. The most common constituents of the dissolved load are bicarbonate ions (HCC>3$^-$), sulfate ions (S0$_4^2$~), calcium ions (Ca^{2+}), sodium ions (Na^+), and magnesium ions (Mg^+). As discussed in Chapter 3, an ion is an atom or molecule with a positive or negative charge resulting from a gain or loss of electrons. Typically the above five ions constitute more than 90 percent of a river's dissolved load. It is the suspended and bed loads of streams that, when deposited in undesirable locations, produce the sediment pollution discussed in Chapter 13.

8.4 River Velocity, Discharge, Erosion, and Sediment Deposition

Rivers are the basic transportation system of that part of the rock cycle involving erosion and deposition of sediments. They are a primary erosion agent in the sculpting of our landscape. The velocity, or speed, of the water in a river varies along its course, affecting both erosion and deposition of sediment.

Discharge (Q) is the volume of water moving by a particular location in a river per unit time. It is reported in cubic meters per second (cms) or cubic feet per second (cfs). Discharge is calculated as

$$Q = W \times D \times V$$

where Q is discharge (cubic meters per second), W is the width of flow in meters, D is depth of flow in meters, and V is mean velocity of flow (meters per second). The equation $Q = W \times D \times V$ is known as the **continuity equation** and is one of the most important relationships in understanding the flow of water in rivers. We assume that if there are no additions or deletions of flow along a given length of river, then discharge is constant. It follows then that if the cross-sectional area of flow ($W \times D$) decreases, then the velocity of the water must increase. You can observe this change with a garden hose. Turn on the water and observe the velocity of the water as it exits the hose. Then put your thumb partly over the end of the hose, reducing the area where the water flows out of the hose, and observe the increase in the velocity. This concept explains why a narrow river channel in a canyon has a higher velocity of flow. It is also the reason that rapids are common in narrow canyons. In general, a faster-flowing river has the ability to erode its banks more than a slower-moving one. Streams that flow from mountains onto plains may form fan-shaped deposits known as *alluvial fans* (Figure 8.8). Rivers flowing into the ocean or some other body of still water may deposit sediments that form a *delta,* a triangular or irregular-shaped landmass extending into the sea or a lake (Figure 8.9). The flood hazard associated with alluvial fans and deltas is different from hazards in a river valley and floodplain environment because rivers entering alluvial fan or delta environments often split into a system of *distributary channels.* That is, the river no longer has only one main channel but has several channels that carry floodwaters to different parts of the fan or delta. Furthermore, these channels characteristically may change position rapidly during floods, producing a flood hazard that is difficult to predict. For example, a large recreational vehicle (RV) park on the delta of the Ventura River in southern California flooded four times in the 1990s. The RV park was constructed across a historically active distributary channel of the Ventura River. However, before the construction of the park, the engineers mapping the potential flood hazards on the site did not recognize that the park was located on a delta. This story emphasizes the importance of studying a river's flooding history as part of flood hazard evaluation (see A Closer Look: History of a River).

Figure 8.8 Alluvial Fan Alluvial fan along the western foot of the Black Mountains, Death Valley. Note the road along the base of the fan. The white materials are salt deposits in Death Valley. *(Michael Collier)*

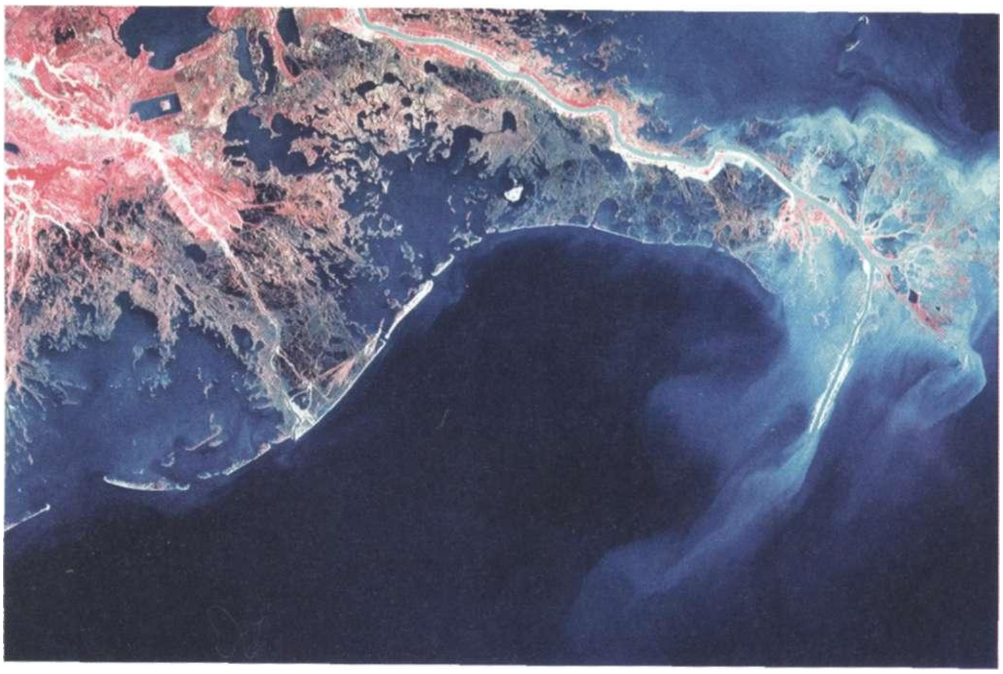


Figure 8.9 Delta The delta of the Mississippi River. In this false-color image, vegetation appears red and sediment-laden waters are white or light blue; deeper water with less suspended sediment is a darker blue. The system of distributary channels in the delta in the far right of the photograph looks something like a bird's foot, and, in fact, the Mississippi River delta is an example of a bird's-foot delta. The distributary channels carry sediment out into the Gulf of Mexico, and, because wave action is not strong in the gulf, the river dominates the delta system. Distance across the image is about 180 km (112 mi). Other rivers flow into a more active coastal environment. Such deltas have a relatively straight coastline, rather than bird's foot shaped, and are considered to be wave dominated. Other deltas are between the end points of river domination and wave domination, as for example the Nile, delta with its beautiful triangular shape, with convex shoreline protruding into the Mediterranean Sea. *(LANDSAT image by U.S. Geological Survey/Courtesy of John S. She/ton)*

A CLOSER LOOK History of a River

In 1905 philosopher George Santayana said, "Those who cannot remember the past are condemned to repeat it." Scholars may debate the age-old question of whether cycles in human history repeat themselves, but the repetitive nature of natural hazards such as floods is undisputed.[8] Better understanding of the historical behavior of a river is therefore valuable in estimating its present and future flood hazards. Consider the February 1992 Ventura River flood in southern California. The flood severely damaged the Ventura Beach Recreational Vehicle (RV) Resort, which had been constructed a few years earlier on an active distributary channel of the Ventura River delta. Although the recurrence interval is approximately 22 years (Figure 8.A), earlier engineering studies suggested that the RV park would not be inundated by flood with a recurrence interval of 100 years. What went wrong?

- Planners did not recognize that the RV park was constructed on a historically active distributary channel of the Ventura River delta. In fact, early reports did not even mention a delta.
- Engineering models that predict flood inundation are inaccurate when evaluating distributary channels on river deltas where extensive channel fill and scour as well as lateral movement of the channel are likely to occur.
- Historical documents such as maps dating back to 1855 and more-recent aerial photographs that showed the channels were not evaluated. Figure 8.B shows that maps rendered from these documents suggest that the distributary channel was in fact present in 1855.[9]

Clearly, the historical behavior of the river was not evaluated as part of the flood-hazard evaluation. If it had been, the site would have been declared unacceptable for development, given that a historically active channel was present. Nevertheless, necessary permits were issued for development of the park, and, in fact, the park was rebuilt after the flood. Before 1992, the distributary channel carried discharges during 1969, 1978, and 1982. After the 1992 flood event, the channel carried floodwaters in the winters of 1993, 1995, and 1998, again flooding the RV park. During the 1992 floods, the discharge increased from less than 25 m^3 per second (883 ft^3 per second) to a peak of 1,322 m^3 per second (46,683 ft^3 per second) in only about 4 hours! This is approximately twice as much as the daily high discharge of the Colorado River through the Grand Canyon in the summer, when it is navigated by river rafters. This is an incredible discharge for a relatively small river with a drainage area of only about 585 km^2 (226 mi^2). The flood occurred during daylight, and one person was killed. If the flood had occurred at night, many more deaths would have been recorded. A warning system that has been developed for the park has, so far, been effective in providing early warning of an impending flood. The park, with or without the RVs and people, is a "sitting duck." Its vulnerability was dramatically illustrated in 1995 and 1998, when winter floods again swept through the park. Although the warning system worked and the park was successfully evacuated, the facility was again severely damaged. There is now a movement afoot to purchase the park and restore the land to a more natural delta environment: a good move!

Figure 8.A Flooding of California's Ventura Beach RV Resort in February 1992 The RV park was built directly across a historically active distributary channel of the Ventura River delta. The recurrence interval of this flood is approximately 22 years. A similar flood occurred again in 1995. Notice that U.S. Highway 101 along the Pacific Coast is completely closed by the flood event. *(Mark J. Terrell/AP/Wide World Photos)*

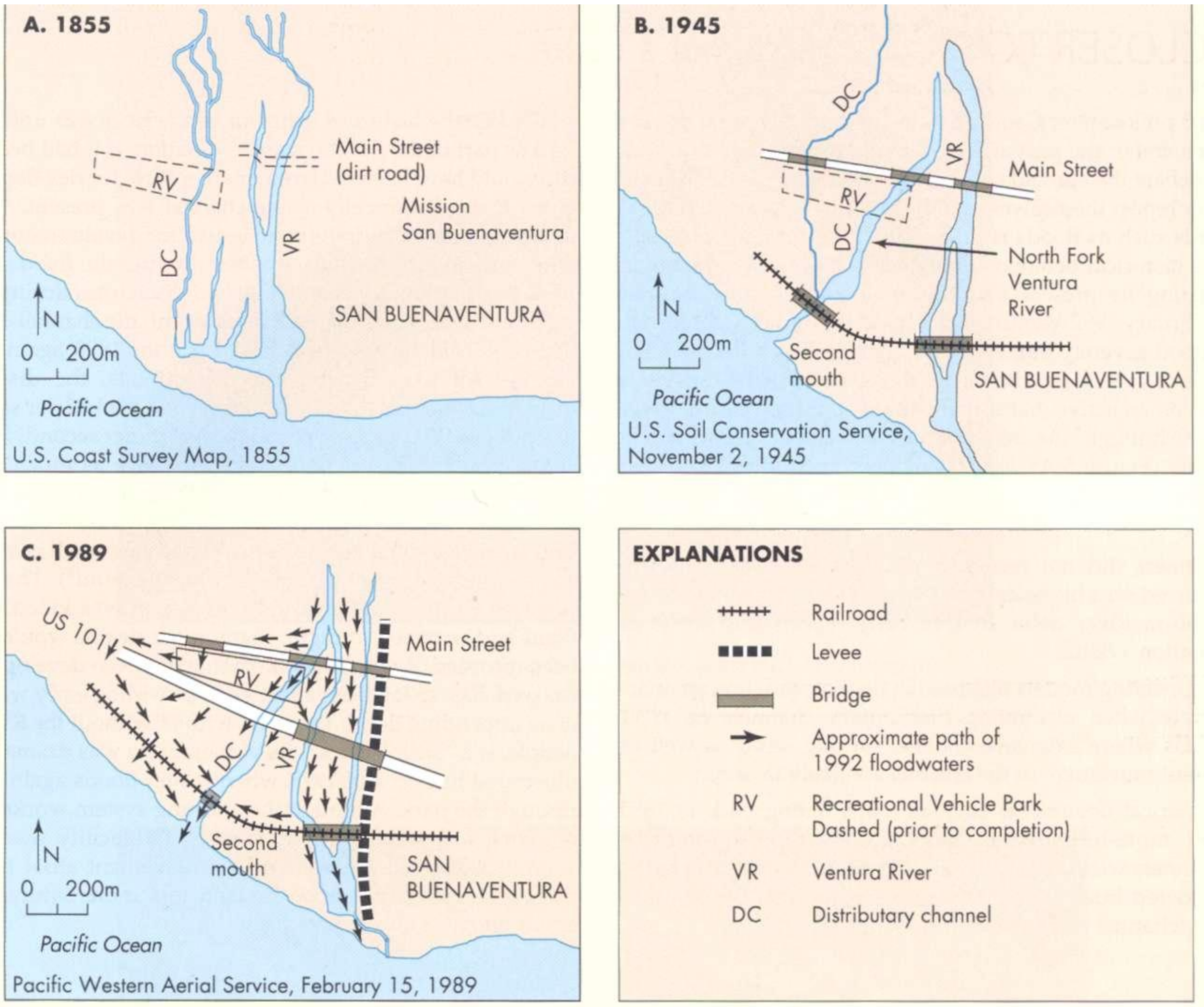


Figure 8.B Historical maps of the Ventura River delta The maps shows the distributary channel and the location of the RV park. *(From Keller, E. A., and Capelli, M. H. 1992. Ventura River flood of February,* 1992: *A lesson ignored?* Water Resources Bulletin *28(5):813-31)*

The reasons erosion or deposition occurs in a specific area of river channel or on alluvial fans or deltas are complex, but they can be correlated to the physical properties of the river:

- Change in channel width, depth, or slope
- Composition of channel bed and banks (rock, gravel, sand, silt, or clay)
- Type and amount of vegetation
- Land use such as clearing forest for agriculture (discussed in Section 8.5)

For example, deposition on alluvial fans occurs in part because of changes in the shape and slope of distributary channels. They often become wider and shallower with a decreasing slope, and this change decreases the velocity of flow, favoring deposition. In general, as the velocity of flow in a river increases, the size of the bed load it can transport increases, as does the volume of suspended load consisting of silt and clay-sized particles. Specific relationships between flow velocity, discharge, and sediment transport are beyond the scope of our discussion here.

The largest particle (diameter in millimeters or centimeters) a river may transport is called its *competency;* the total load, by mass or weight, of sediment that a river carries in a given period of time is called its *capacity.*

8.5 Effects of Land-Use Changes

Streams and rivers are open systems that generally maintain a rough *dynamic equilibrium,* or steady state between the work done, that is, the sediment transported by the stream, and the load imposed, or the sediment delivered to the stream from tributaries and hill slopes. The stream tends to have a slope and cross-sectional shape that provide the velocity of flow necessary to do the work of moving the sediment load.[10] An increase or decrease in the amount of water or sediment received by the stream usually brings about changes in the channel's slope or cross-sectional shape, effectively changing the velocity of the water. The change of velocity may, in turn, increase or decrease the amount of sediment carried in the system. Therefore, land-use changes that affect the stream's volume of sediment or water volume may set into motion a series of events that results in a new dynamic equilibrium.

Consider, for example, a land-use change from forest to agricultural row crops. This change will cause increased soil erosion and an increase in the sediment load supplied to the stream because agricultural lands have higher soil erosion rates than forested lands. At first, the stream will be unable to transport the entire load and will deposit more sediment, increasing the slope of the channel. The steeper slope of the channel will increase the velocity of water and allow the stream to move more sediment. If the base level is fixed, the slope will continue to increase by deposition in the channel until the increase in velocity is sufficient to carry the new load. If the notion that deposition of sediment increases channel slope is counterintuitive to you, see Figure 8.10 for an illustration of this principle. A new dynamic equilibrium may be reached, provided the rate of sediment increase levels out and the channel slope and shape can adjust before another land-use change occurs. Suppose the reverse situation now occurs; that is, farmland is converted to forest. The sediment load to the stream from the land will decrease, and less sediment will be deposited in the stream channel. Erosion of the channel will eventually lower the slope; the lowering of the slope will, in turn, lower the velocity of the water. The predominance of erosion over deposition will continue until equilibrium between the total load imposed and work done is achieved again.

The sequence of change just described occurred in parts of the southeastern United States. On the Piedmont, between the Appalachian Mountains and the coastal plain, forestland had been cleared for farming by the 1800s. The land-use change from forest to farming accelerated soil erosion and subsequent deposition

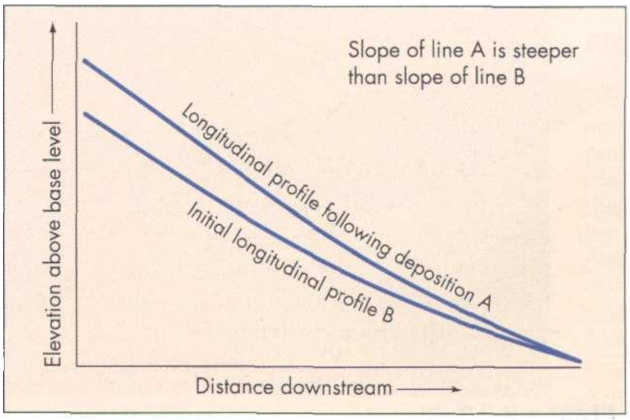


Figure 8.10 Effect of deposition on river slope Idealized diagram illustrating that deposition in a stream channel results in an increase in channel gradient.

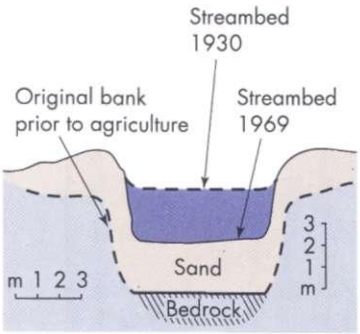


Figure 8.11 Stream bed changes from land use changes Accelerated sedimentation and subsequent erosion resulting from land-use changes (natural forest to agriculture and back to forest) at the Mauldin Millsite on the Piedmont of middle Georgia. *(After Trimble, S. W. 1969. "Culturally accelerated sedimentation on the middle Georgia Piedmont." Master's thesis, Athens: University of Georgia. Reproduced by permission)*

of sediment in the stream (Figure 8.11). This acceleration caused the preagriculture channel to fill with sediment, as shown in Figure 8.11. After 1930, the land reverted to pine forests, and this reforestation, in conjunction with soil conservation measures, reduced the sediment load delivered to streams. Thus, formerly muddy streams choked with sediment had cleared and eroded their channels by 1969 (Figure 8.11).

Consider now the effect of constructing a dam on a stream. Considerable changes will take place both upstream and downstream of the reservoir created behind the dam. Upstream, at the head of the reservoir, the water in the stream will slow down, causing deposition of sediment. Downstream, the water coming out below the dam will have little sediment, since most of it has been trapped in the reservoir. As a result, the stream may have the capacity to transport additional sediment; if this happens, channel erosion will predominate over deposition downstream of the dam. The slope of the stream will then decrease until new equilibrium conditions are reached (Figure 8.12). (We will return to the topic of dams on rivers in Chapter 12.)

8.6 Channel Patterns and Floodplain Formation

The configuration of the channel as seen in an aerial view is called the channel pattern. Channel patterns can be braided or meandering, or both characteristics-may be found in the same river. *Braided* channels (Figure 8.13) are characterized by numerous gravel bars and islands that divide and reunite the channel. A steep slope and coarse sediment favor transport of bed load material important in the development of gravel bars that form the "islands" that divide and subdivide the flow. The formation of the braided channel pattern, as with many other river forms, results from the interaction of flowing water and moving sediment. If the river's longitudinal profile is steep and there is an abundance of coarse bed load sediment, the channel pattern is likely to be braided. Braided channels tend to be wide and shallow compared with meandering rivers. They are often associated with steep rivers flowing through areas that are being rapidly uplifted by tectonic processes. They are also common in rivers receiving water from melting glaciers that provide a lot of coarse sediment.

Some channels contain *meanders,* which are bends that migrate back and forth across the floorplain (Figure 8.14a). Although we know what meander bends look like and what the water and sediment do in the bends, we do not know for sure why rivers meander. On the outside of a bend, sometimes referred to as the *cut bank,* the water moves faster during high flow events, causing more bank erosion; on the inside of a curve water moves more slowly and sediment is deposited, forming *point bars.* As this differential erosion and sediment deposition continues, meanders migrate laterally by erosion on the cut banks and by deposition on point

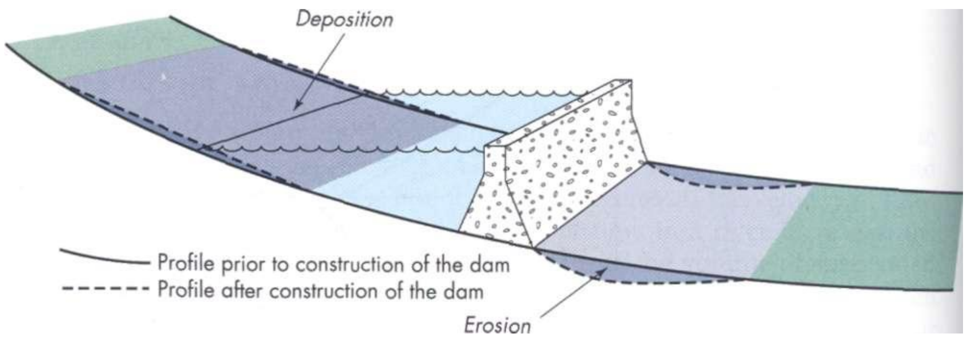
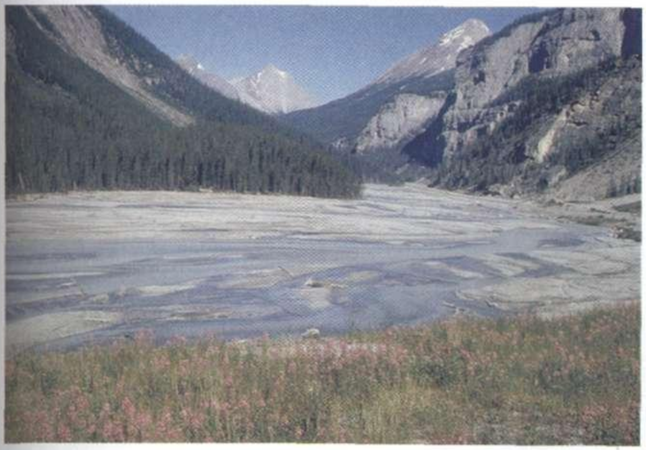


Figure 8.12 Effect of a dam on erosion Upstream deposition and downstream erosion from construction of a dam and a reservoir.



(a)

(b)

Figure 8.13 Braided channels (a) The north Saskatchewan River, shown here, has a braided channel pattern. Notice the numerous channel bars and islands that subdivide the flow. *(John S. Shelton)* (b) Ground view of a braided channel in Granada in southern Spain with multiple channels, a steep gradient, and coarse gravel. The distance across the channel is about 7 m (21 ft). *(Edward A. Keller)*

(a)

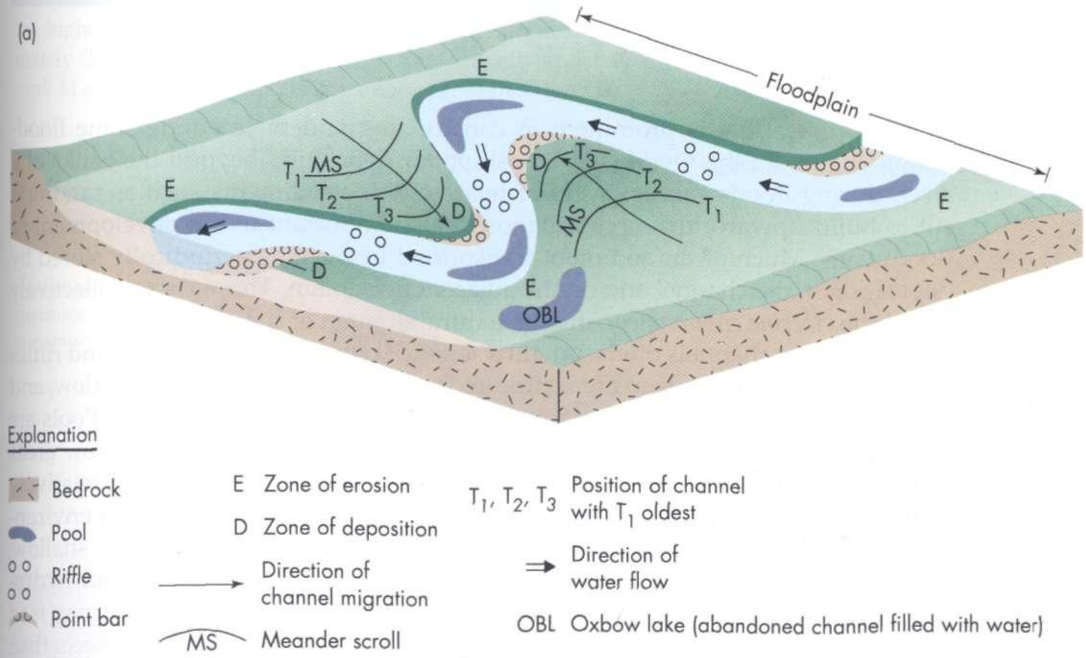


Figure 8.14 Meandering river (a) Idealized diagram of a meandering stream and important forms and processes. Meander scrolls are low, curved ridges of sediment parallel to a meander bend. They form at the edge of a riverbank as sediment accumulates with plants. A series of scrolls marks the evolution of a meander bend, (b) Koyakuk River, Alaska, showing meander bend, point bar, and cut bank. The Oxbow Lake formed as the river eroded laterally across the floodplain and "cut off" a meander bend, leaving the meander bend as a lake. (© Andy *Deering/Omni-Photo Communications, Inc.)*

Figure 8.15 Pool and riffle Well-developed pool-riffle sequence in Sims Creek near Blowing Rock, North Carolina. A deep pool is apparent in the middle distance, and shallow riffles can be seen in the far distance and in the foreground. *(Edward A. Keller)*

bars, a process that is prominent in constructing and maintaining some floodplains (Figure 8.14b). Overbank deposition, or deposition beyond the banks of a river, during floods causes layers of relatively fine sediments such as sand and silt to build upward; this accumulation is also important in the development of floodplains. Much of the sediment transported in rivers is periodically stored by deposition in the channel and on the adjacent floodplain. These areas, collectively called the *riverine environment,* are the natural domain of the river.

Meandering channels often contain a series of regularly spaced pools and riffles (Figure 8.15). *Pools* are deep areas produced by scour, or erosion at high flow, and characterized at low flow by relatively deep, slow movement of water. Pools are places in which you might want to take a summer swim. *Riffles* are shallow areas produced by depositional processes at high flow and characterized by relatively shallow, fast-moving water at low flow. Pools and riffles have important environmental significance: The alternation of deep, slow-moving water with shallow, fast-moving water in pools and riffles produces a variable physical and hydrologic environment and increased biological diversity.[11] For example, fish may feed in riffles and seek shelter in pools, and pools have different types of insects than are found in riffles.

Having presented some of the characteristics and processes of flow of water and sediment in rivers, we will now discuss the process of flooding in greater detail.

8.7 River Flooding

The natural process of *overbank flow* is termed flooding (see Figure 8.6). Most river flooding is a function of the total amount and distribution of precipitation in the drainage basin, the rate at which precipitation infiltrates the rock or soil, and the topography. Some floods, however, result from rapid melting of ice and snow in the spring, on rare occasions, from the failure of a dam. Finally, land use can greatly affect flooding in small drainage basins.

The channel discharge at the point where water overflows the channel is called the flood discharge and is used as an indication of the magnitude of the flood (see A Closer Look: Magnitude and Frequency of Floods). The height of the water in a

A CLOSER LOOK Magnitude and Frequency of Floods

Flooding is intimately related to the amount and intensity of precipitation and runoff. Catastrophic floods reported on television and in newspapers are often produced by infrequent, large, intense storms. Smaller floods or flows may be produced by less intense storms, which occur more frequently. All flow events that can be measured or estimated from a stream-gauging station (Figure 8.C) can be arranged in order of their magnitude of discharge, generally measured in cubic meters per second (Figure 8.D). The list of annual peak flows—that is, the largest flow each year or the annual series so arranged (see data for the Patrick River on table adjacent to Figure 8.E)—can be plotted on a discharge-frequency curve by deriving the recurrence interval (R) for each flow from the relationship

$$R = (N + 1)/M$$

where R is a recurrence interval in years, N is the number of years of record, and M is the rank of the individual flow within the recorded years (Figure 8.E).[13] For example, in Figure 8.E the highest flow for 9 years of data for the stream is approximately 280 m^3 per second (9,888 ft^3 per second) and has a rank M equal to 1.[14] The recurrence interval of this flood is

$$R = \frac{N+1}{M} = \frac{9+1}{1} = 10 \text{ yr}$$

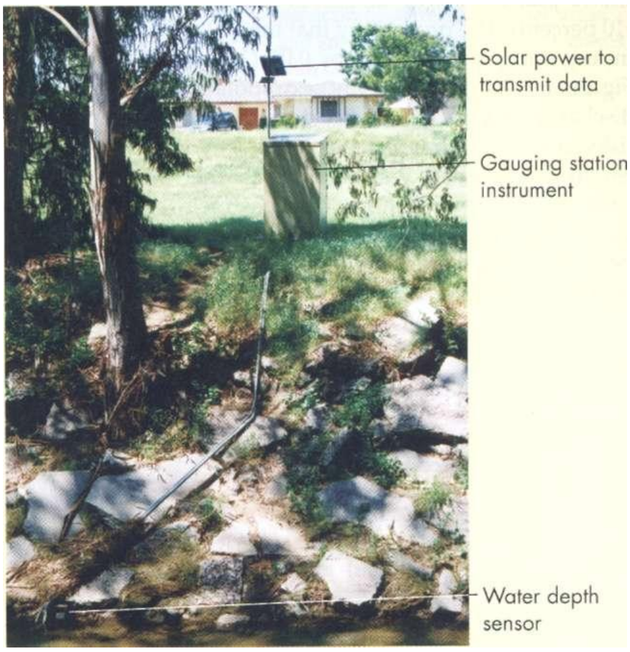


Figure 8.C Stream-gauging station San Jose Creek, Goleta, California. *(Edward A. Keller)*

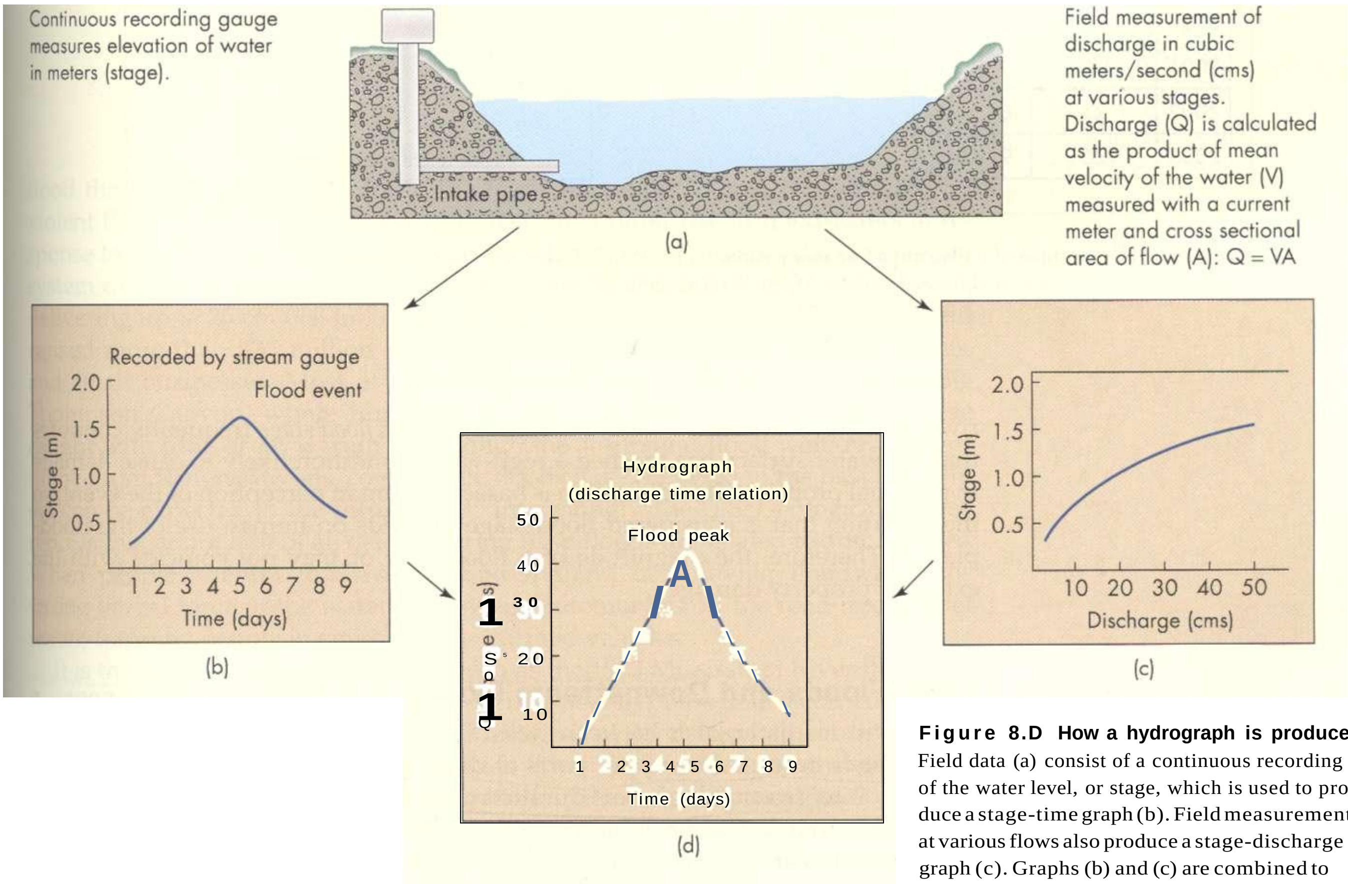


Figure 8.D How a hydrograph is produced Field data (a) consist of a continuous recording of the water level, or stage, which is used to produce a stage-time graph (b). Field measurements at various flows also produce a stage-discharge graph (c). Graphs (b) and (c) are combined to produce the final hydrograph (d).

which means that a flood with a magnitude equal to or exceeding 280 m^3 per second can be expected about every 10 years; we call this a 10 year flood. The probability that the 10 year flood will happen in any one year is 1/10, or 0.1 (10 percent). The probability that the 100 year flood will occur in any one year is 1/100, or 0.01 (1 percent). The curve in Figure 8.E is extended by extrapolation to estimate the discharge of the 20 year flood at 450 cms. Extrapolation is risky and shouldn't extend much beyond two times the length of recorded values of discharge. Studies of many streams and rivers show that channels are formed and maintained by bankfull discharge, defined as a flow with a recurrence interval of about 1.5 years (27 m^3 per second in Figure 8.E). Bankfull is the flow that just fills the channel. Therefore, we can expect a stream to emerge from its banks and cover part of the floodplain with water and sediment once every year or so.

As flow records are collected, we can more accurately predict floods. However, designing structures for a 10 year, 25 year, 50 year, or even 100 year flood, or, in fact, any flow, is a calculated risk since predicting such floods is based on a statistical probability. In the long term, a 25 year flood happens on the average of once every 25 years, but two 25 year floods could occur in any given year, as could two 100 year floods![15] As long as we continue to build dams, highways, bridges, homes, and other structures without considering the effects on flood-prone areas, we can expect continued loss of lives and property.

Patrick River Stream Gauge Data Peak Annual Flow

Year	Discharge (cms)	M	R (yrs)
1995	30	5	2
1996	280	1	10
1997	45	4	2.5
1998	28	6	1.7
1999	120	2	5
2000	26	7	1.4
2001	100	3	3.3
2002	23	8	1.3
2003	20	9	1.1

M = Magnitude where M = 1 is the highest flow on record

R = Recurrence Interval in years; calculated by $R = \frac{N+1}{M}$; for Patrick River N = 9

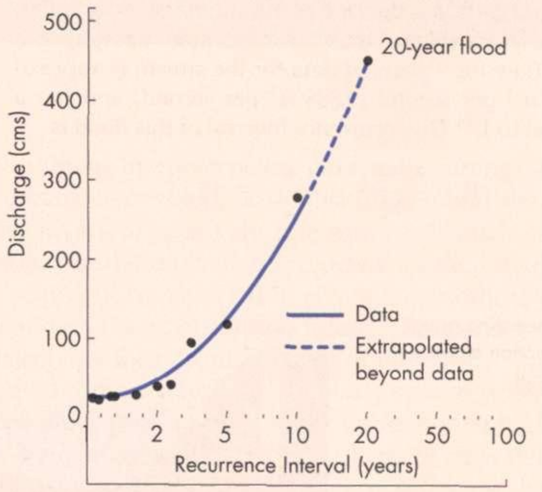


Figure 8.E Example of a discharge-frequency curve for the Patrick River on the adjacent table. The curve is extended (extrapolated) to estimate the 20 year flood at about 450 cms.

river at any given time is called the *stage*. The term *flood stage* frequently connotes that the water surface has reached a high-water condition likely to cause damage to personal property. This definition is based on human perception of the event, so the elevation that is considered flood stage depends on human use of the floodplain.[12] Therefore, the magnitude of a flood may or may not coincide with the extent of property damage.

Flash Floods and Downstream Floods

It is useful to distinguish between flash and downstream floods (Figure 8.16). **Flash floods** occur in the upper parts of drainage basins and are generally produced by intense rain
flash floods rnay not cause flooding in the larger streams they Join downstream, although they can be quite severe locally. For example, the high-magnitude flash

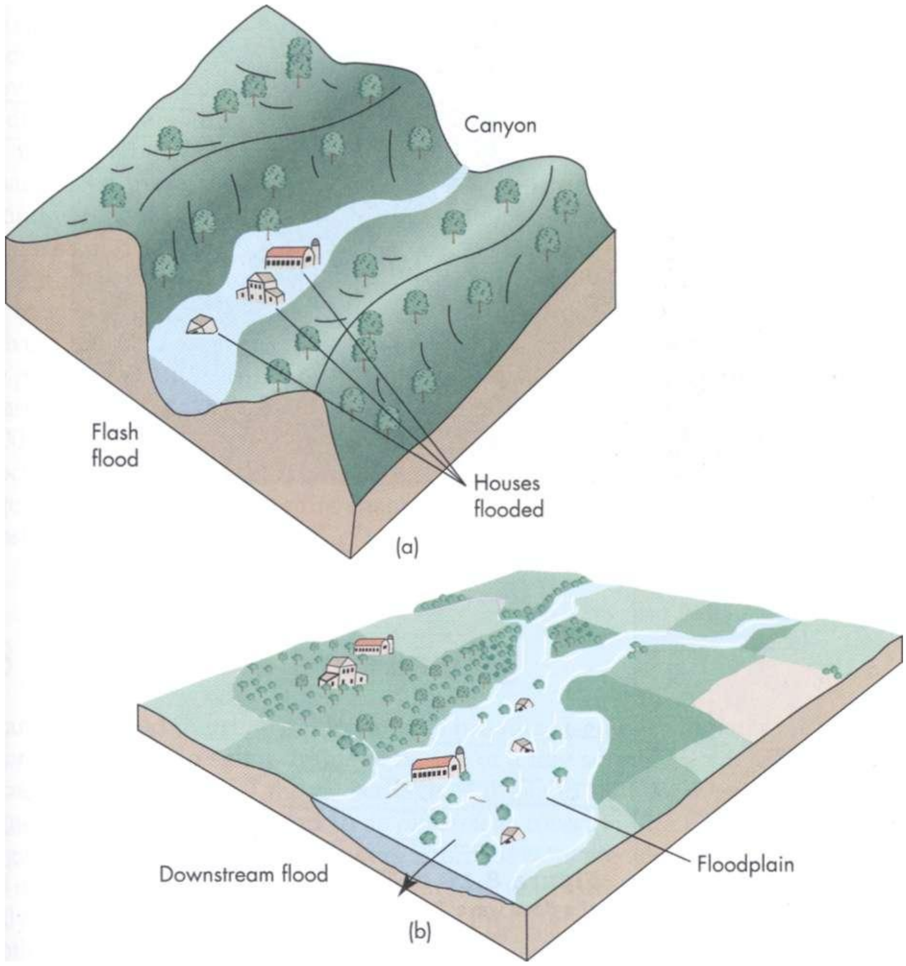


Figure 8.16 Flash floods and downstream floods Idealized diagram comparing flash flood (a) with a downstream flood (b). Flash floods generally cover relatively small areas and are caused by intense local storms with steep topography, often in a canyon. A distinct floodplain may not be present, whereas downstream floods cover wide areas of a floodplain and are caused by regional storms or spring runoff of a floodplain. *(Modified after U.S. Department of Agriculture drawing)*

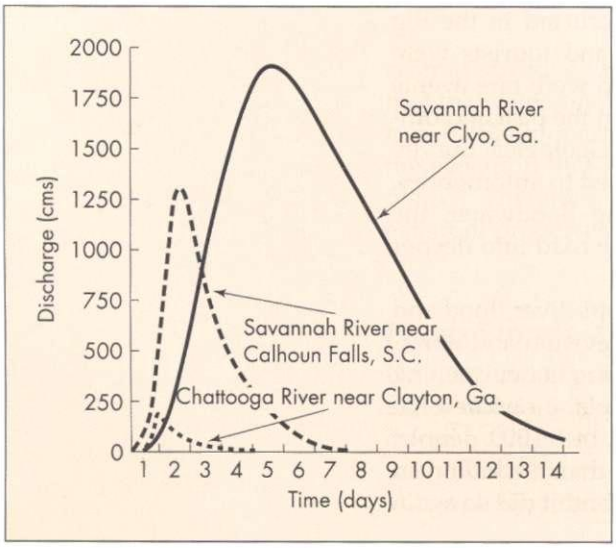
flood that occurred in July 1976 in the Front Range of Colorado was caused by violent flash floods, which are characterized by a rapid rise in floodwaters in response to precipitation. In addition, the flash floods were nourished by a complex system of thunderstorms that swept through several canyons west of Loveland, delivering up to 25 cm (9.8 in.) of rain. This brief local flood killed 139 people and caused more than $35 million in damages to highways, roads, bridges, homes, and small businesses. Most of the damage and loss of life occurred in the Big Thompson Canyon, where hundreds of residents, campers, and tourists were caught with little or no warning. Although the storm and flood were rare events in the Front Range canyons, comparable floods have occurred in the past and others can be expected in the futute.[16,17,18] Interestingly, the U.S. Geological Survey reports that about half of all deaths during flash floods are related to automobiles. When people attempt to drive through shallow, fast-moving floodwater, the strong lateral force of the water may sweep automobiles off the road into deeper water, trapping people in sinking or overturned vehicles.

It is the large downstream floods, such as the 1993 Mississippi River flood and the 1997 Red River, North Dakota, flood that usually make television and newspaper headlines. We discussed the 1993 Mississippi River flooding in our opening case. Floodwaters of the Red River, which flows north to Canada, inundated the city of Grand Forks, North Dakota, initiating the evacuation of 50,000 people, causing a fire that burned part of the city center and more than $1 billion in damage (Figure 8.17). The Red River often floods in the spring, and it did so again

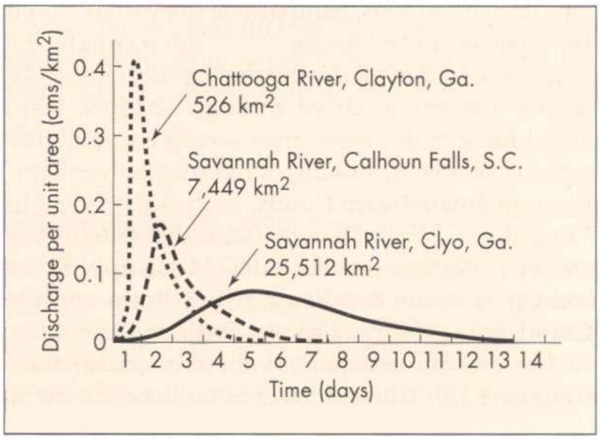
Figure 8.17 Flooded city Flooding of the Red River at Grand Forks, North Dakota, in 1997 caused a fire that burned part of the city. *(Eric Hylden/Grand Forks Herald)*

(a)

Figure 8.18 Downstream movement of a flood wave Downstream movement of a flood wave on the Savannah River, South Carolina and Georgia. The distance from Clayton to Clyo is 257 km (160 mi), (a) Map of the area, (b) Volume of water passing Clayton, Calhoun Falls, and Clyo. (c) Volume of water per unit area at the same points. *(After Hoyt, W. G., and Langbein, W. B.* Floods. *© Copyright 1955 by Princeton University Press, figure 8, p. 39. Reprinted by permission of Princeton University Press)*



(b)



(c)

in the spring of 2001 when heavy rains melted snow and ice on frozen ground that did not allow infiltration of the rain into the forest.

Downstream floods cover a wide area and are usually produced by storms of long duration that saturate the soil and produce increased runoff. Flooding on small tributary basins is limited, but the contribution of increased runoff from thousands of tributary basins may cause a large flood downstream. A flood of this kind is characterized by the downstream movement of the floodwaters with a large rise and fall of discharge at a particular location.[19] Figure 8.18a shows an area map and 8.18b shows the 257 km (160 mi) downstream migration of a flood crest on the Chattooga-Savannah River system. It illustrates that a progressively longer time is necessary for the rise and fall of water as the flood wave proceeds downstream. In addition, it dramatically shows the tremendous increase in discharge from low-flow conditions to more than 1,700 m^3 per second (60,000 ft^3 per second) in 5 days.[20] Figure 8.18c illustrates the same flood in terms of discharge per unit area, eliminating the effect of downstream increase in discharge. This better illustrates the shape and form of the flood wave as it moves downstream.[20]

8,8 Urbanization and Flooding

Human use of land in urban environments has increased both the magnitude and frequency of floods in small drainage basins of a few square kilometers. The rate of increase is a function of the percentage of the land that is covered with roofs, pavement, and cement, referred to as *impervious cover* (Figure 8.19), and the percentage of area served by storm sewers.. Storm sewers die important Because they allow urban runoff from impervious surfaces to reach stream channels much more quickly than in natural settings. Therefore, impervious cover and storm sewers are collectively a measure of the degree of urbanization. The graph in Figure 8.20 shows that an urban area with 40 percent impervious surface and 40 percent of its area served by storm sewers can expect to have about three times as many floods as before urbanization. This ratio applies to floods of small and intermediate frequency. As the size of the drainage basin increases, however, high-magnitude floods with frequencies of approximately 50 years are not significantly affected by urbanization (Figure 8.21).

Floods are a function of rainfall-runoff relations, and urbanization causes a tremendous number of changes in these relationships. One study showed that urban runoff from the larger storms is nearly five times th

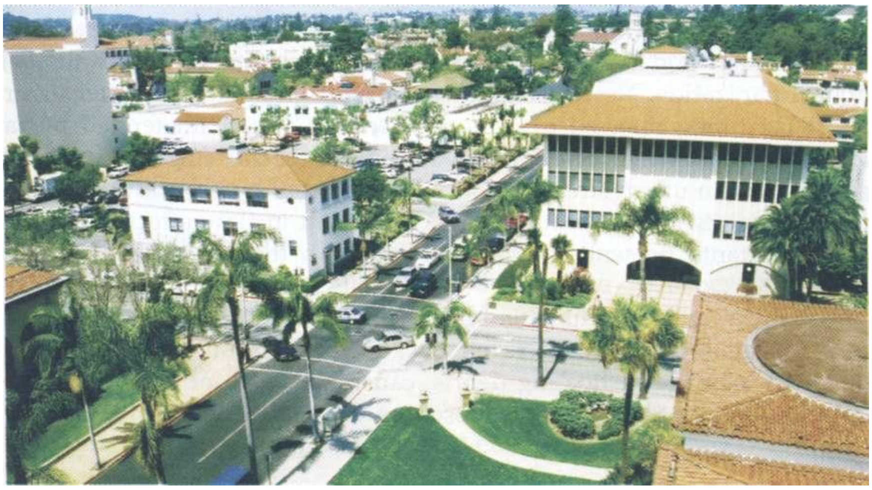


Figure 8.19 Urbanization increases runoff Cities in most of the United States, such as Santa Barbara, California, shown here, have a high portion of their land covered by roofs, streets, and parking lots. These surfaces do not allow water to infiltrate the ground so surface runoff greatly increases. *(Edward A. Keller)*

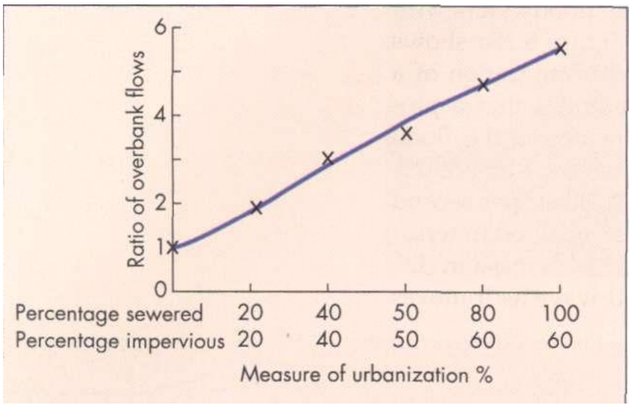


Figure 8.20 **Floods before and after urbanization** Relationship between the ratio of overbank flows (after urbanization to before urbanization) and measure of urbanization. For example, a ratio of 3 to 1, or simply 3, means that after urbanization there are three floods for every one there was before urbanization; or flooding is three times as common after urbanization. This figure shows that as the degree of urbanization increases, the number of overbank flows per year also increases. *(After Leopold, L. B. 1968. U.S. Geological Survey Circular 559)*

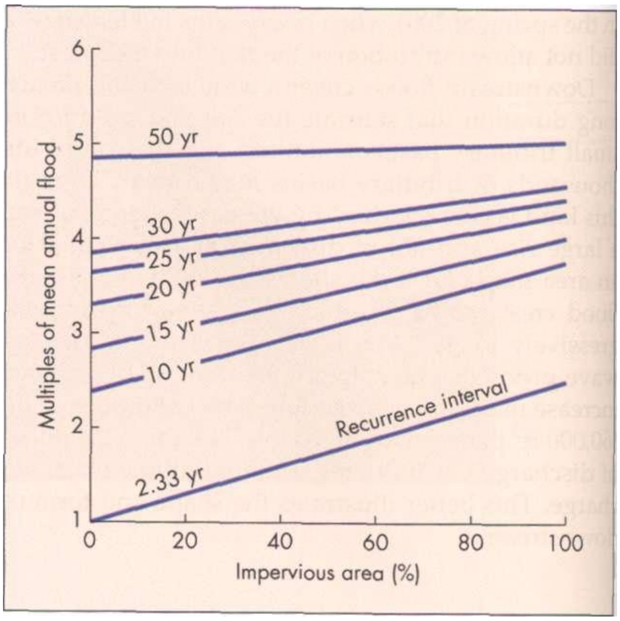


Figure 8.21 **Urban flood hazard increases as impervious area increases** Graph showing the variation of flood frequency with percentage of impervious area. The mean annual flood (approximately bankfull) is the average (over a period of years) of the largest flow that occurs each year. The mean annual flood in a natural river basin with no urbanization has a recurrence interval of 2.33 years. Note that the smaller floods with recurrence intervals of just a few years are much more affected by urbanization than are the larger floods. The 50-year flood is little affected by the amount of area that is rendered impervious. *(From Martens, L. A. 1968. U.S. Geological Survey Water Supply Paper 1591C)*

Estimates of discharge for different recurrence intervals at different degrees of urbanization are shown in Figure 8.22. The estimates clearly indicate the tremendous increase of runoff with increasing impervious areas and storm sewer coverage. However, it is not only the peak discharge that causes urban flooding. Long-duration storms resulting from moderate precipitation can also cause flooding if storm drains become blocked with sediment and storm debris. In this case, water begins to pond, causing flooding in low areas. It is analogous to water rising in a bathtub shower when the drain becomes partly blocked by soap.

Urbanization causes increased runoff because less water infiltrates the ground. Figure 8.23a shows a generalized hydrograph before urbanization. Of particular importance is the *lag time,* defined as the time between when most of the rainfall occurs and a flood is produced. Figure 8.23b shows two hydrographs, before and after urbanization. Note the significant reduction in lag time after urbanization. Short lag times, referred to as *flashy discharge,* are characterized by rapid rise and fall of floodwater. Since little water infiltrates the soil, the low water or dry-season flow in urban streams, normally sustained by groundwater seepage into the channel, is greatly reduced. This reduction in flow effectively concentrates any pollutants present and generally lowers the aesthetic amenities of the stream.[14]

Urbanization is not the only type of development that can increase flooding. Some flash floods have occurred because bridges built across small streams block the passage of floating debris, causing a wave of water to move downstream when the debris breaks loose (see Case History: Flash Floods in Eastern Ohio).

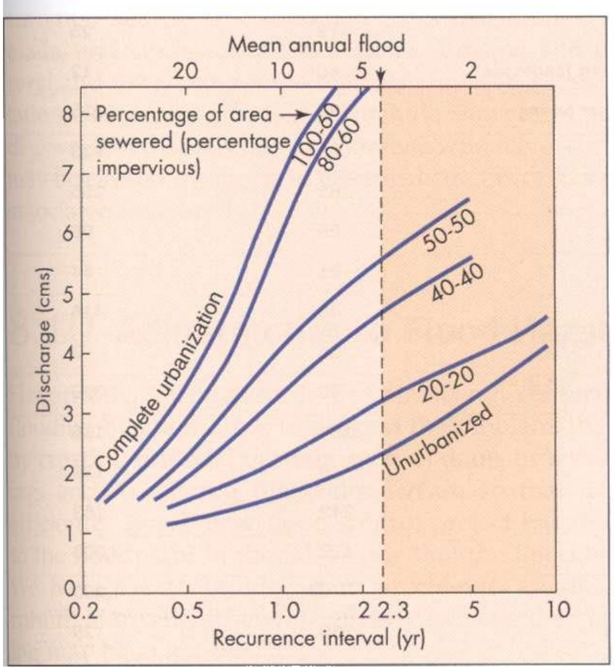


Figure 8.22 Urbanization increases flood for a particular recurrence interval Flood frequency curve for a 2.6-km^2 (1-mi^2) basin in various states of urbanization. 100-60 means the basin is 100 percent sewered and 60 percent of surface area is impervious. The dashed line shows the increase in mean annual flood with increasing urbanization. *(After Leopold, L. B. 1968. U.S. Geological Survey Circular 559)*

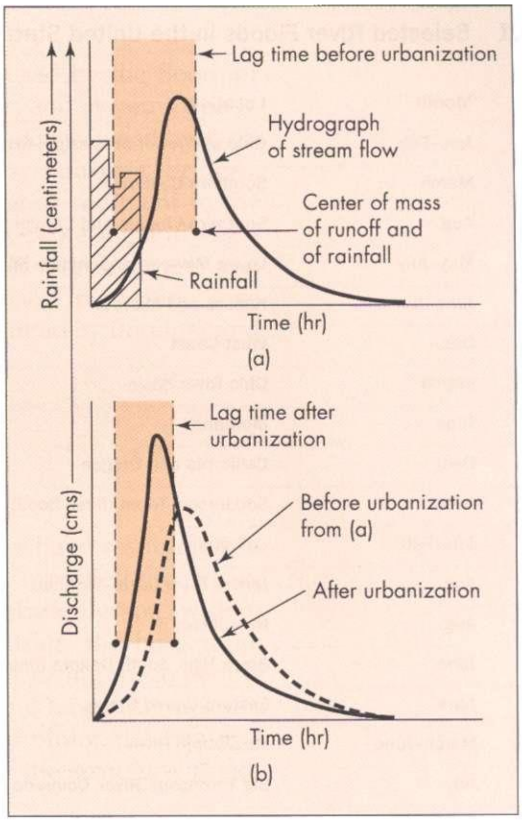


Figure 8.23 Urbanization shortens lag time Generalized hydrographs. (a) Hydrograph shows the typical lag between the time when most of the rainfall occurs and the time when the stream floods, (b) Here, the hydrograph shows the decrease in lag time because of urbanization. *(After Leopold, L. B. 1968. U.S. Geological Survey Circular 559)*

8.9 The Nature and Extent of Flood Hazards

Flooding is one of the most universally experienced natural hazards. In the United States, floods were the number one type of disaster during the twentieth century, and approximately 100 lives per year (or about 10,000 in the twentieth century) are lost because of river flooding. Tragically, this figure is low compared with losses suffered by developing countries that lack monitoring facilities, warning systems, and effective disaster relief.[12,22] Table 8.1 lists some severe river floods that occurred in the United States from 1937 to 2006.

Factors That Cause Flood Damage

Factors that affect the damage caused by floods include

- Land use on the floodplain
- Magnitude, or the depth and velocity of the water and frequency of flooding
- Rate of rise and duration of flooding
- Season, for example, growing season on the floodplain
- Sediment load deposited
- Effectiveness of forecasting, warning, and emergency systems

TABLE 8.1 Selected River Floods in the United States

Year	Month	Location	No. of Lives Lost	Property Damage (Millions of Dollars)
1937	Jan.-Feb.	Ohio and lower Mississippi River basins	137	418
1938	March	Southern California	79	25
1940	Aug.	Southern Virginia and Carolinas and eastern Tennessee	40	12
1947	May-July	Lower Missouri and middle Mississippi River basins	29	235
1951	June-July	Kansas and Missouri	28	923
1955	Dec.	West Coast	61	155
1963	March	Ohio River basin	26	98
1964	June	Montana	31	54
1964	Dec.	California and Oregon	40	416
1965	June	Sanderson, Texas (flash flood)	26	3
1969	Jan.-Feb.	California	60	399
1969	Aug.	James River basin, Virginia	154	116
1971	Aug.	New Jersey	3	139
1972	June	Black Hills, South Dakota (flash flood)	242	163
1972	June	Eastern United States	113	3,000
1973	March-June	Mississippi River	0	1,200
1976	July	Big Thompson River, Colorado (flash flood)	139	35
1977	July	Johnstown, Pennsylvania	76	330
1977	Sept.	Kansas City, Missouri, and Kansas	25	80
1979	April	Mississippi and Alabama	10	500
1983	Sept.	Arizona	13	416
1986	Winter	Western states, especially California	17	270
1990	Jan.-May	Trinity River, Texas	0	1,000
1990	June	Eastern Ohio (flash flood)	21	Several
1993	June-Aug.	Mississippi River and tributaries		
1997	January	Sierra Nevada, Central Valley, California	23	Several hundred
2001	June	Houston, Texas. Buffalo Bayou (coastal river)	22	2,000
2006	June-July	Mid-Atlantic states, New York to North Carolina	16	100+

CASE HISTORY Flash Floods in Eastern Ohio

On Friday, June 15, 1990, over 14 cm (5.5 in.) of precipitation fell within approximately 4 hours in some areas of eastern Ohio. Two tributaries of the Ohio River, Wegee and Pipe Creeks, generated flash floods near the small town of Shadyside, killing 21 people and leaving 13 people missing and presumed dead. The floods were described as 5 m (16 ft) high walls of water that rushed through the valley. In all, approximately 70 houses were destroyed and another 40 were damaged. Trailers and houses were seen washing down the creeks, bobbing like corks in the torrent.

The rush of water was apparently due to the failure of debris dams that had developed across the creeks upstream of bridges. Runoff from rainfall had washed debris into the creeks from side slopes; this debris, including tree trunks and other material, became lodged against the bridges, creating the debris dams. When the bridges could no longer contain the weight of the debris, the dams broke loose, sending surges of water downstream. This scenario has been played and replayed in many flash floods around the world. All too often, the supports for bridges are too close together to allow large debris to pass through; instead the debris accumulates on the upstream side of the bridge, damming the stream and eventually causing a flood.

Effects of Flooding

The effects of flooding may be primary, that is, directly caused by the flood, or secondary, caused by disruption and malfunction of services and systems due to the flood.[22] Primary effects include injury, loss of life, and damage caused by swift currents, debris, and sediment to farms, homes, buildings, railroads, bridges, roads, and communication systems. Erosion and deposition of sediment in the rural and urban landscape may also involve a loss of considerable soil and vegetation. Secondary effects may include short-term pollution of rivers, hunger and disease, and displacement of persons who have lost their homes. In addition, fires may be caused by shorts in electrical circuits or gas mains broken by flooding and associated erosion.[22]

8.10 Adjustments to Flood Hazards

Historically, particularly in the nineteenth century, humans have responded to flooding by attempting to prevent the problem; that is, they modified the stream by creating physical barriers such as dams or levees or by straightening, widening, and deepening the entire stream so that it would drain the land more efficiently. Every new flood control project has the effect of luring more people to the floodplain in the false hope that the flood hazard is no longer significant. We have yet to build a dam or channel capable of controlling the heaviest runoff, and when the water finally exceeds the capacity of the structure, flooding may be extensive.[22,23]

In recent years, we have begun to recognize the advantages of alternative adjustments to trying to physically prevent flooding. These include flood insurance and controlling the land use on floodplains. We will discuss each of the main adjustments with the realization that no one adjustment is best in all cases. Rather, an integrated approach to minimizing the flood hazard that incorporates the appropriate adjustments for a particular situation is preferable.

The Structural Approach

Physical Barriers. Measures to prevent flooding include construction of physical barriers such as levees (Figure 8.24) and floodwalls, which are usually

Figure 8.24 Mississippi River levee A levee with a road on top of it protects the bank (left side of photograph) of the lower Mississippi River at this location in Louisiana. *(Comstock Images)*

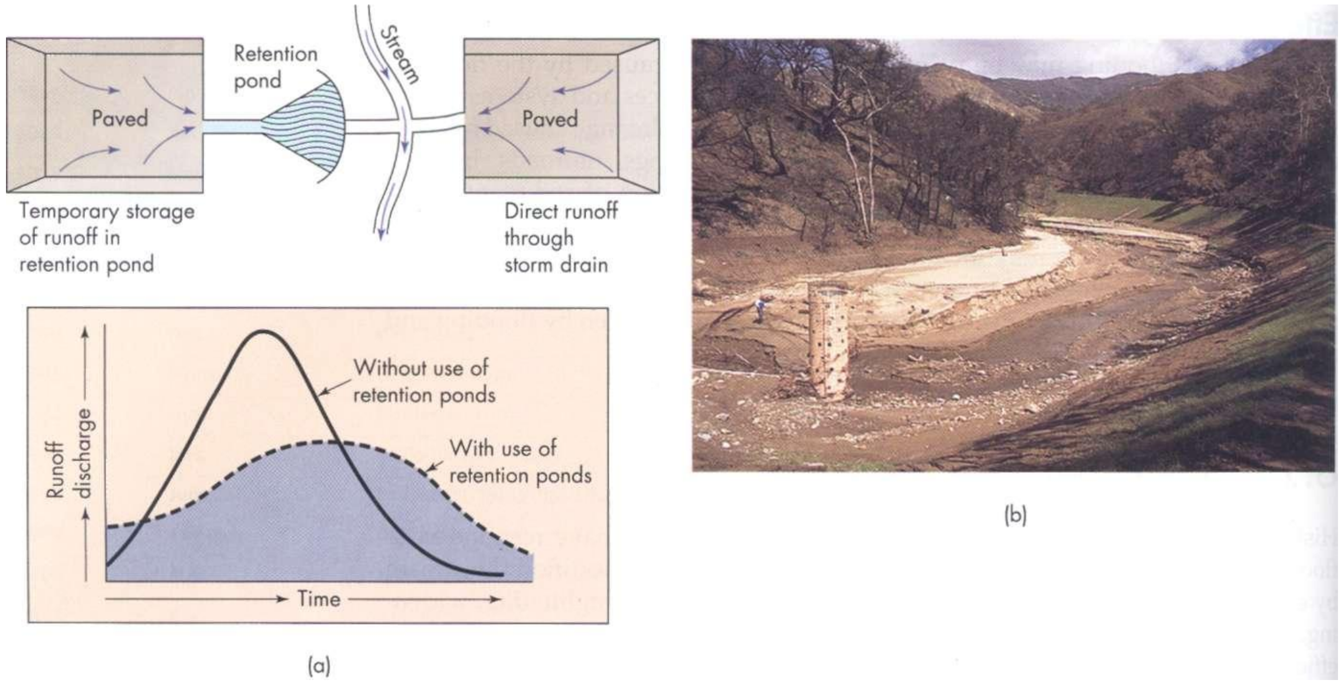


Figure 8.25 Retention pond (a) Comparison of runoff from a paved area through a storm drain with runoff from a paved area through a temporary storage site (retention pond). Notice that the paved area drained by way of the retention pond produces a lesser peak discharge and therefore is less likely to contribute to flooding of the stream. *(Modified after U.S. Geological Survey Professional Paper 950)* (b) Photograph of a retention pond near Santa Barbara, California. *(Edward A. Keller)*

constructed of concrete as opposed to earthen levees; reservoirs to store water for later release at safe rates; and on-site stormwater retention basins (Figure 8.25). Unfortunately, the potential benefits of physical barriers are often lost because of increased development on floodplains that are supposedly protected by these structures. For example, the winters of 1986 and 1997 brought tremendous storms and flooding to the western states, particularly California, Nevada, and Utah. In all, damages exceeded several hundred million dollars and several people died. During one of the storms and floods in 1986, a levee broke on the Yuba River in California, causing more than 20,000 people to flee their homes. An important lesson learned during this flood is that levees constructed along rivers many years ago are often in poor condition and subject to failure during floods.

The 1997 floods damaged campsites and other development in Yosemite National Park. As a result, the park revised its floodplain management policy; some camping and other facilities were abandoned, and the river is now allowed to "run free."

Some engineering structures designed to prevent flooding have actually increased the flood hazard in the long term. For example, as discussed in the case history opening this chapter, floodwalls produced a bottleneck at St. Louis that increased upstream flooding during the 1993 floods of the Mississippi River (Figure 8.2).

Recurring flooding, particularly on the Mississippi, has led to the controversial speculation that human activities have contributed to an increase in flooding. Over time equal flood discharge is producing higher flood stages. The systems of levees, floodwalls, and structures to improve river navigation for barges transporting goods down river control the smaller floods. For the largest floods, these same systems may constrain or retard flow (slow it down) and this results in higher levels of flood flow (stage).[26]

After observing causes and effects of many floods, we have learned that structural controls must go hand in hand with floodplain regulations if the hazard is to be minimized.[1,23,24,25]

Channelization. Straightening, deepening, widening, clearing, or lining existing stream channels are all methods of **channelization.** Basically, it is an engineering technique, with the objectives of controlling floods, draining wetlands, controlling erosion, and improving navigation.[27] Of the four objectives, flood control and drainage improvement are the two most often cited in channelization projects. Thousands of kilometers of streams in the United States have been modified, and thousands of kilometers of channelization are now being planned or constructed. Federal agencies alone have carried out several thousand kilometers of channel modification. In the past, however, inadequate consideration has been given to the adverse environmental effects of channelization.

Opponents of channelizing natural streams emphasize that the practice is antithetical to the production of fish and wetland wildlife and, furthermore, the stream suffers from extensive aesthetic degradation. The argument is as follows:

- Drainage of wetlands adversely affects plants and animals by eliminating habitats necessary for the survival of certain species.
- Cutting trees along the stream eliminates shading and cover for fish and exposes the stream to the sun; the exposure results in damage to plant life and heat-sensitive aquatic organisms.
- Cutting hardwood trees on the floodplain eliminates the habitats of many animals and birds, while facilitating erosion and siltation of the stream.
- Straightening and modifying the streambed destroy both the diversity of flow patterns and the feeding and breeding areas for aquatic life while changing peak flow.
- Conversion of wetlands from a meandering stream to a straight, open ditch seriously degrades the aesthetic value of a natural area.[27] Figure 8.26 summarizes some of the differences between natural streams and those modified by channelization.

Not all channelization causes serious environmental degradation; in many cases, drainage projects are beneficial. Benefits are probably best observed in urban areas subject to flooding and in rural areas where previous land use has caused drainage problems. In addition, there are other examples in which channel modification has improved navigation or reduced flooding and has not caused environmental disruption.

Channel Restoration: Alternative to Channelization

Many streams in urban areas scarcely resemble natural channels. The process of constructing roads, utilities, and buildings with the associated sediment production is sufficient to disrupt most small streams. **Channel restoration**[28] uses various techniques: cleaning urban waste from the channel, allowing the stream to flow freely, protecting the existing channel banks by not removing existing trees or, where necessary, planting additional native trees and other vegetation. Trees provide shade for a stream, and the root systems protect the banks from erosion (Figure 8.27). The objective is to create a more natural channel by allowing the stream to meander and, when possible, provide for variable, low-water flow conditions: fast and shallow flow on riffles alternating with slow and deep flow in pools. Where lateral bank erosion must be absolutely controlled, the outsides of

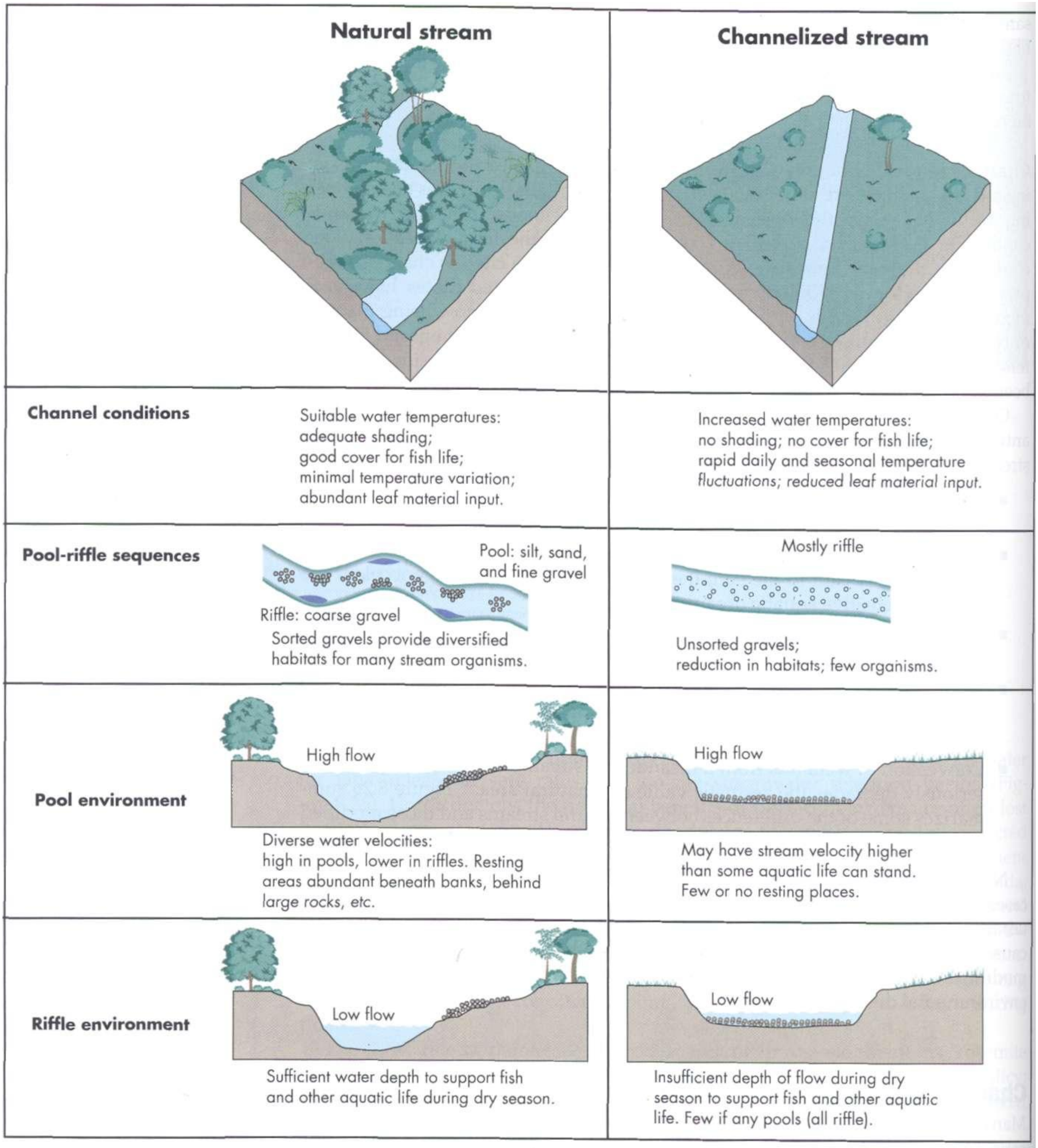


Figure 8.26 Natural versus channelized stream A natural stream compared with a channelized stream in terms of general characteristics and pool environments. *(Modified after Corning,* Virginia Wildlife, *February 1975)*

bends may be defended with large stones known as *riprap.* Design criteria for channel restoration are shown on Figure 8.28.

River restoration of the Kissimmee River in Florida may be the most ambitious restoration project ever attempted in the United States (see Chapter 4).[29] In Los Angeles, California, a group called Friends of the River has suggested that

Figure 8.27 Tree roots protecting stream bank from erosion *(Edward A. Keller)*

the Los Angeles River be restored. This will be a difficult task since most of the riverbed and banks are lined with concrete (Figure 8.29). However, a river park is planned for one section of the river where a more natural-looking channel has reappeared since channelization (Figure 8.30).

Flood Insurance

In 1968, when private companies became reluctant to continue to offer flood insurance, the federal government took over. The U.S. National Flood Insurance

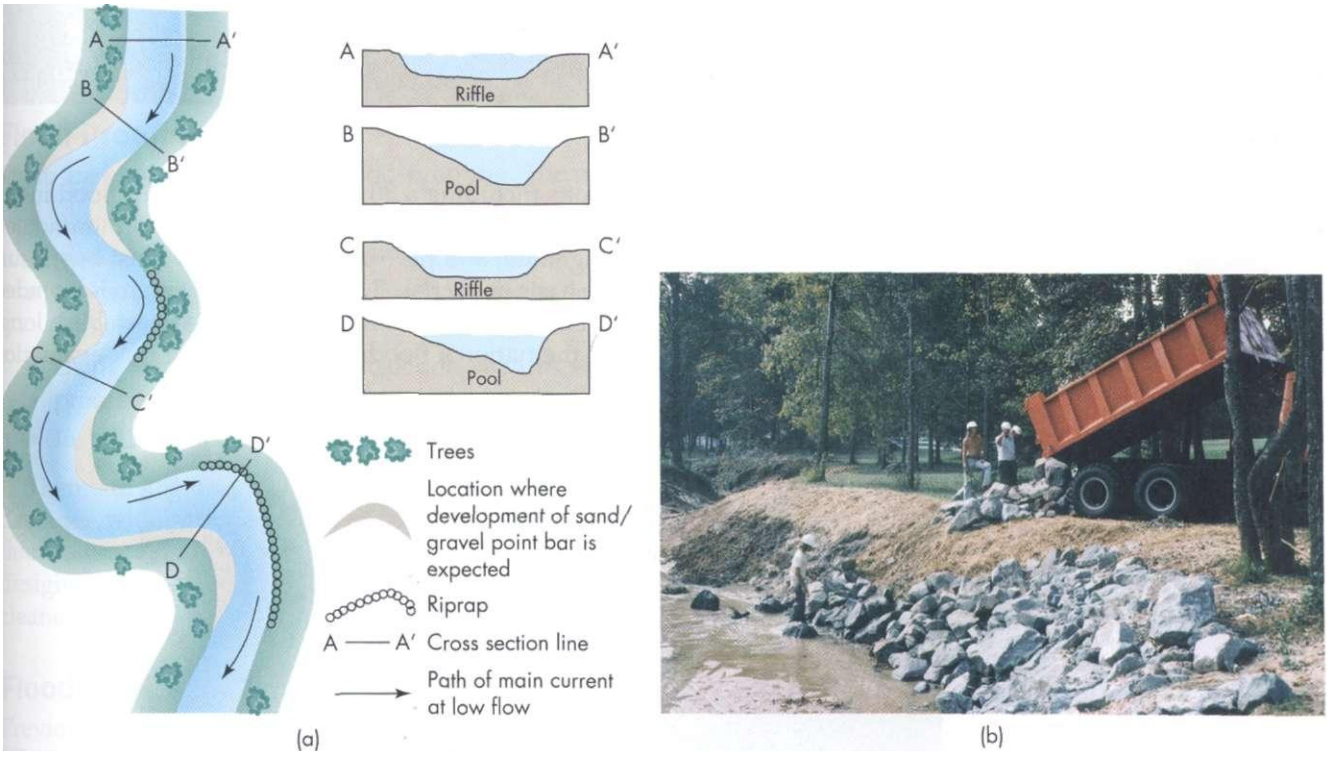


Figure 8.28 Urban stream restoration (a) Channel-restoration design criteria for urban streams, using a variable channel shape to induce scour and deposition (pools and riffles) at desired locations. *(Modified after Keller, E. A., and Hoffman, E. K. 1977.* Journal of Soil and Water Conservation *32(5):237-40)*
(b) Placing riprap where absolutely necessary to defend the bank, Briar Creek, Charlotte, North Carolina. Notice the planting of grass on banks with straw mulch and trees growing on banks. *(Edward A. Keller)*

(a)

(b)

Figure 8.29 Channelization versus restoration (a) Concrete channel in Los Angeles River system compared with (b) channel restoration in North Carolina. *(Edward A. Keller)*

Program makes, with restrictions including a 30 day waiting period, flood insurance available at subsidized rates. Special Flood Hazard Areas, those inundated by the 100 year flood, are designated, and new property owners must buy insurance at rates determined on the basis of the risk. The insurance program is intended to provide short-term financial aid to victims of floods as well as to establish long-term land-use regulations for the nation's floodplains. The basic risk evaluation

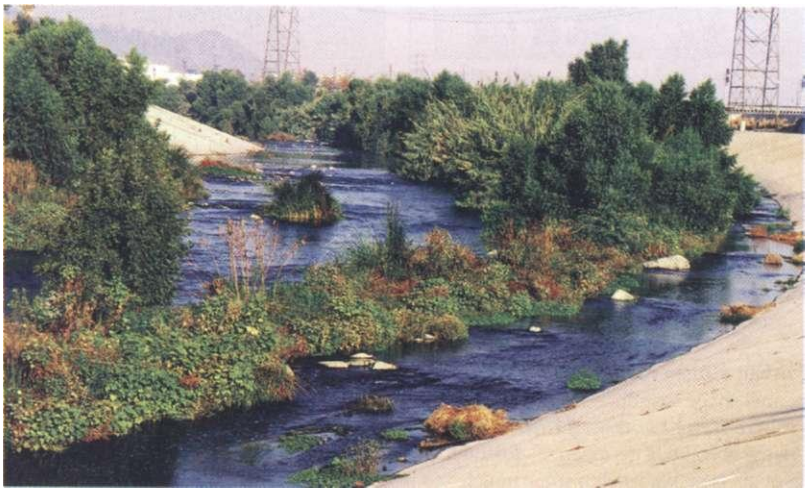


Figure 8.30 Los Angeles River Part of the Los Angeles River where a more natural channel has developed since channelization. *(Deirdra Walpole Photography)*

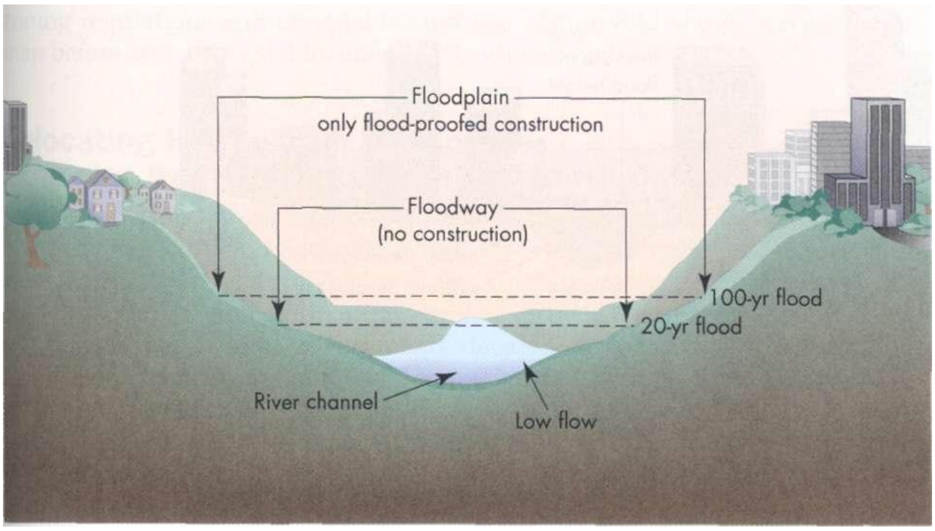


Figure 8.31 Floodplain regulation Idealized diagram showing areas inundated by the 100 and 20 year floods used in the U.S. National Flood Insurance Program.

centers on identifying the floodplain area inundated by the 100 year flood. Only flood-proofed buildings are allowed in this area (Figure 8.31), and no construction is allowed on the portion of the floodplain inundated by the 20 year flood. For a community to join the National Flood Insurance Program, it must adopt minimum standards of land-use regulation within the 100 year floodplain, mapped by the Federal Emergency Management Agency (FEMA). Nearly all communities with a flood risk in the United States have basic flood hazard maps and have initiated some form of floodplain regulations. Several million insurance policies are presently held by property owners.[30]

By the early 1990s, it was recognized that the insurance program was in need of reform, resulting in the National Flood Insurance Reform Act of 1994. The act was passed to encourage opportunities to mitigate flood hazards, including flood-proofing, relocations, and buy-outs of properties likely to be frequently flooded.[30]

Flood-Proofing

There are several methods of flood-proofing. The most common include

- Raising the foundation of a building above the flood hazard level by using piles or columns or by extending foundation walls or earth fill[30]
- Constructing floodwalls or earth berms around buildings to seal them from floodwaters
- Using waterproofing construction such as waterproofed doors and waterproofed basement walls and windows
- Installing improved drains with pumps to keep flood waters out

There are also modifications to buildings that are designed to minimize flood damages while allowing floodwaters to enter a building. For example, ground floors along expansive riverfront properties in some communities in Germany are designed so that they are not seriously damaged by floodwaters and may be easily cleaned and made ready for reuse after a flood.[30]

Floodplain Regulation

Previously we have defined the floodplain as a landform produced by a river. When we try to regulate development on a flood-hazard area we often define the floodplain from a hydrologic point of view. Thus the 100 year floodplain is that part of a river valley that is inundated by the 100 year flood. For a particular river at a particular site that flood has a discharge (volume of flow per unit time such as cubic meters or cubic feet per second). We often determine that discharge from analyzing past flow records (see A Closer Look: Magnitude and Frequency of Floods).

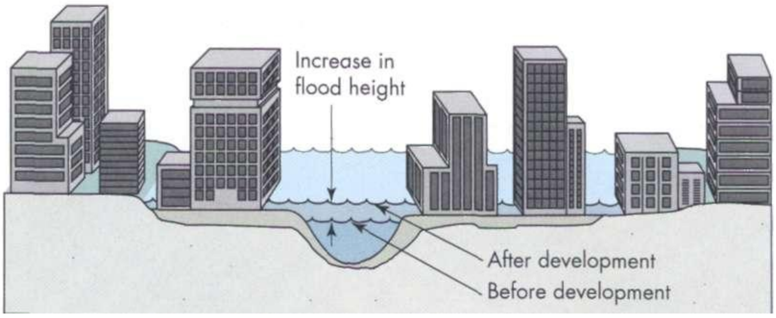


Figure 8.32 Increasing flood hazard Development that encroaches on the floodplain can increase the heights of subsequent floods. (From *Water Resources Council. 1971.* **Regulation of flood hazard areas,** *vol. 1)*

From an environmental point of view, the best approach to minimizing flood damage in urban areas is **floodplain regulation.** The big problem is that several million people in nearly 4,000 U.S. towns and cities live on floodplains with a recognized flood hazard. The objective of floodplain regulation is to obtain the most beneficial use of floodplains while minimizing flood damage and cost of flood protection.[31] Floodplain regulation is a compromise between indiscriminate use of floodplains, resulting in loss of life and tremendous property damage, and complete abandonment of floodplains, which gives up a valuable natural resource.

This is not to say that physical barriers, reservoirs, and channelization works are not desirable. In areas developed on floodplains, they will be necessary to protect lives and property. We need to recognize, however, that the floodplain belongs to the river system, and any encroachment that reduces the cross-sectional area of the floodplain increases flooding (Figure 8.32). An ideal solution would be discontinuing floodplain development that necessitates new physical barriers. In other words, the ideal is to "design with nature." Realistically, the most effective and practical solution in most cases will be a combination of physical barriers and floodplain regulations that results in fewer physical modifications of the river system. For example, reasonable floodplain zoning in conjunction with a diversion channel project or upstream reservoir may result in a smaller diversion channel or reservoir than would be necessary without floodplain regulations.

Flood-Hazard Mapping

A preliminary step to floodplain regulation is flood-hazard mapping, which is a means of providing information about the floodplain for land-use planning.[32] Flood-hazard maps may delineate past floods or floods of a particular frequency, for example, the 100 year flood (Figure 8.31). They are useful in regulating private development, purchasing land for public use as parks and recreational facilities, and creating guidelines for future land use on floodplains.

Flood-hazard evaluation may be accomplished in a general way by direct observation and measurement of physical parameters. For example, extensive flooding of the Mississippi River Valley during the summer of 1993 is clearly shown on images produced from satellite-collected data (see Figure 8.2). Floods can also be mapped from aerial photographs taken during flood events; they can be estimated from high-water lines, flood deposits, scour marks, and trapped debris on the floodplain, measured in the field after the water has receded.[3] The most common way we produce flood-hazard maps today is to use mathematical models that show the land flooded by a particular flow—often the 100 year flood.

Floodplain Zoning. Flood-hazard information is used to designate a flood-hazard area. Once the hazard area has been established, planners can establish zoning regulations and acceptable land use. Figure 8.33 shows a typical zoning map before and after establishment of floodplain regulations.

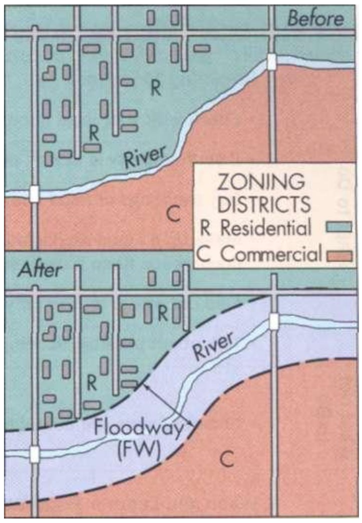


Figure 8.33 Floodplain zoning Typical zoning map before and after the addition of flood regulations. *(From Water* Resources *Council. 1971.* Regulation of flood hazard areas, *vol. 1)*

Relocating People from Floodplains: Examples from North Carolina and North Dakota

For several years state and federal governments have been selectively purchasing homes damaged by floodwaters. The purpose is to remove homes from hazardous areas and thereby reduce future losses. In September 1999, Hurricane Floyd brought nearly 50 cm (20 in.) of rain to the North Carolina region, flooding many areas. State and federal governments decided to spend nearly $50 million to remove about 430 homes in Rocky Mount, North Carolina.

At Churchs Ferry, North Dakota there has been a wet cycle since 1992, causing nearby Devils Lake to rise approximately 8 m (26 ft). The lake has no outlet and this part of the Northern Plains is very flat. As a result, the lake has more than doubled in area and is inundating the land in the vicinity of Churchs Ferry. By late June 2000, the town was all but deserted; the population of the town has shrunk from approximately 100 to 7 people. Most of the people in the town have taken advantage of a voluntary federal buyout plan and have moved to higher ground, many to the town of Leeds, approximately 24 km (15 mi) away. The empty houses left behind will be demolished or moved to safer ground.

The lucrative buyout of $3.5 million seemed to be assured, a "slam dunk." The people who participated in the buyout program were given the appraised value of their homes plus an incentive; most considered the offer too good to turn down. There was also recognition that the town would eventually have come to an end as a result of flooding. Nevertheless, there was some bitterness among the town's population, and not everyone participated. The mayor and the fire chief of the town are among the seven people who decided to stay. The buyout program for Churchs Ferry demonstrated that the process is an emotional one; it is difficult for some people to make the decision to leave their home, even though they know it is likely to be damaged by floodwaters in the relatively near future.

Personal Adjustment: What to Do and What Not to Do

Flooding is the most commonly experienced natural hazard. Although we cannot prevent floods from happening, individuals can be better prepared. Table 8.2 summarizes what individuals can do to prepare for a flood as well as what not to do.

8.11 Perception of Flooding

At the institutional level—that is, at the government and flood-control agency level—perception and understanding of flooding are adequate for planning purposes. On the individual level, however, the situation is not as clear. People are tremendously variable in their knowledge of flooding, anticipation of future flooding, and willingness to accept adjustments caused by the hazard.

Progress at the institutional level includes mapping of flood-prone areas (thousands of maps have been prepared), of areas with a flash-flood potential downstream from dams, and areas where urbanization is likely to cause problems in the near future. In addition, the federal government has encouraged states and local communities to adopt floodplain management plans.[8] Still, planning to avoid the flood hazard by not developing on floodplains or by relocating

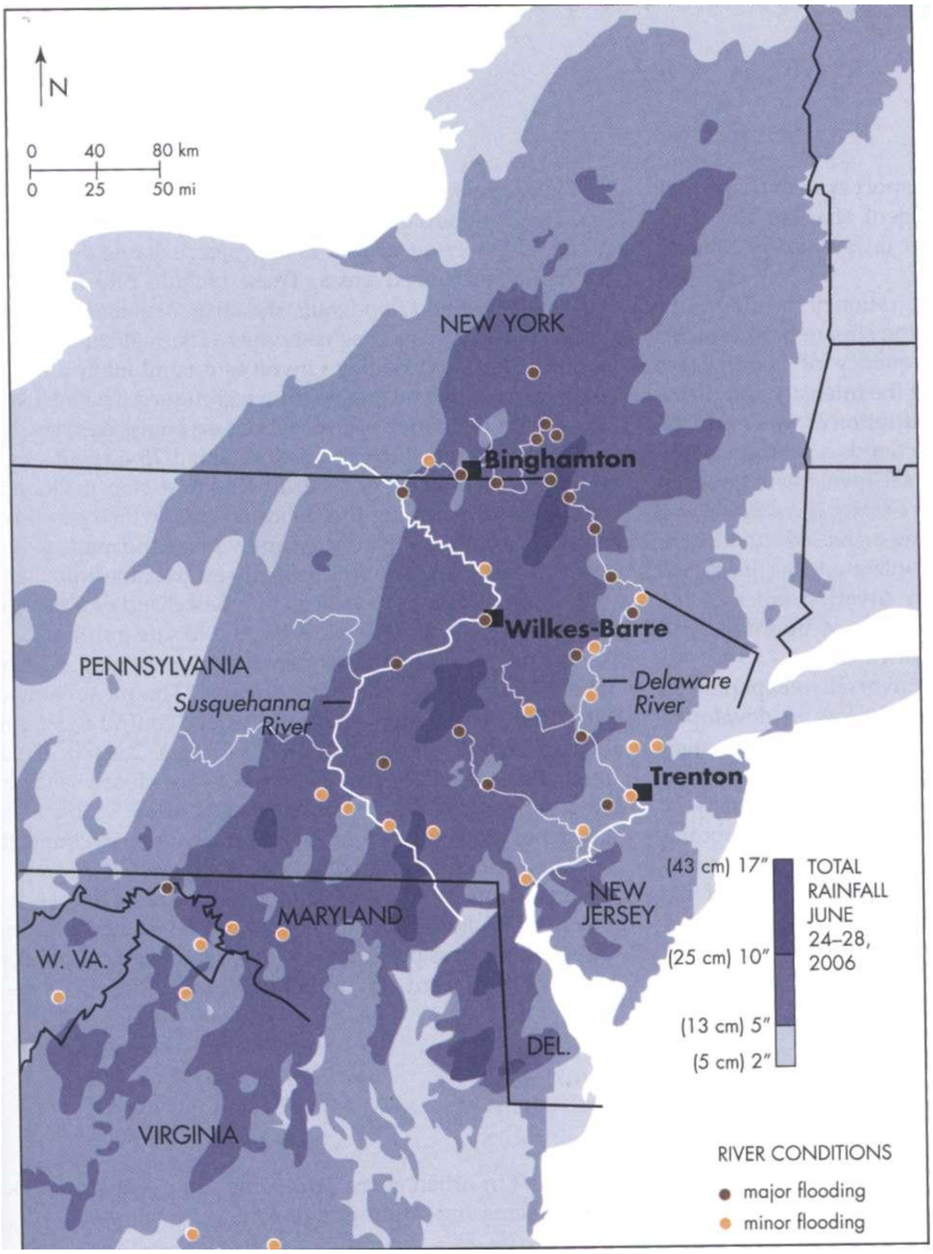
TABLE 8.2 What to Do and What Not to Do before and after a Flood

	Preparing for a Flood
	• Check with your local flood control agency to see if your property is at risk from flooding.
	• If your property is at risk, purchase flood insurance if you can and be sure that you know how to file a claim.
	• Buy sandbags or flood boards to block doors.
	• Make up a Flood Kit, including a flashlight, blankets, raingear, battery-powered radio, first-aid kit, rubber gloves, and key personal documents. Keep it upstairs if possible.
	• Find out where to turn off your gas and electricity. If you are not sure, ask the person who checks your meter when he or she next visits.
	• Talk about possible flooding with your family or housemates. Consider writing a Flood Plan, and store these notes with your Flood Kit.
What Not to Do	• Underestimate the damage a flood can do.
	When You Learn a Flood Warning Has Been Issued
	• Be prepared to evacuate.
	• Observe water levels and stay tuned to radio and television news and weather reports.
	• Move people, pets, and valuables upstairs or to higher ground.
	• Move your car to higher ground. It takes only 0.6 m (2 ft) of fast-flowing water to wash your car away.
	• Check on your neighbors. Do they need help? They may not be able to escape upstairs or may need help moving furniture.
	• Do as much as you can in daylight. If the electricity fails, it will be hard to do anything.
	• Keep warm and dry. A flood can last longer than you think, and it can get cold. Take warm clothes, blankets, a Thermos, and food supplies.
What Not to Do	• Walk in floodwater above knee level: it can easily knock you off your feet. Manholes, road works, and other hazards may be hidden beneath the water.
	After a Flood
	• Check house for damage; photograph any damage.
	• If insured, file a claim for damages.
	• Obtain professional help in removing or drying carpets and furniture as well as cleaning walls and floors.
	• Contact gas, electricity, and water companies. You will need to have your supplies checked before you turn them back on.
	• Open doors and windows to ventilate your home.
	• Wash water taps and run them for a few minutes before use. Your water supply may be contaminated; check with your water supplier if you are concerned.
What Not to Do	• Touch items that have been in contact with the water. Floodwater may be contaminated and could contain sewage. Disinfect and clean thoroughly everything that got wet.

Source: Modified after Environment Agency, United Kingdom. Floodline accessed 11/1/00 at www.environment_agency.gov.uk/flood/press_2.htm

present development to locations off the floodplain needs further consideration and education to be accepted by the general population. This was tragically shown by the 2006 floods in the Mid-Atlantic United States, when severe river flooding impacted the region from Virginia to New York (Figure 8.34). Over 200,000 floodplain residents were evacuated in Pennsylvania alone and damages exceeding $100 million were incurred. About 16 people lost their lives as cars were swept away by floodwaters and people drowned in flood-swollen creeks and rivers. About 70 people were rescued from rooftops. As a people we need to just "say no" to future development on floodplains. That is the most cost-effective way to reduce chronic flooding.

Figure 8.34 Mid-Atlantic floods of June-July 2006 (a) Map of major and minor flooding. *(Modified from New York Times with data from National Weather Service)* (b) Collecting mail from a flooded home in Wilkes-Barre, Pennsylvania. *(AP/Wide World Photos)*



(a)


(b)

Slope Processes, Landslides, and Subsidence

Learning Objectives

Landslides, the movement of materials down slopes, constitute a serious natural hazard in many parts of the United States and the rest of the world. Landslides are often linked to other hazards such as earthquakes and volcanoes. Most landslides are small and slow, but a few are large and fast. Both may cause significant loss of life and damage to human property, particularly in urban areas. In this chapter we focus on the following learning objectives:

- Understand basic slope processes and the causes of slope failure
- Understand the role of driving and resisting forces on slopes and how these are related to slope stability
- Understand how slope angle and topography, vegetation, water, and time affect both slope processes and the incidence of landslides
- Understand how human use of the land has resulted in landslides
- Know methods of identification, prevention, warning, and correction of landslides
- Understand processes related to land subsidence

Landslide La Conchita, California, landslide in 2005 destroyed 13 homes and killed 10 people. *(AP/Wide World Photos)*

CASE HISTORY La Conchita Landslide of 2005

The small beachside community of La Conchita, located about 80 km (50 mi) northwest of Los Angeles, California, was the site of a disaster on January 10, 2005 (see opening photograph). On that day, a fast-moving landslide, debris flow damaged or destroyed 36 homes and killed 10 people. The 2005 landslide was a reactivation of a 1995 landslide that destroyed several homes but caused no deaths. Both the 1995 and 2005 events were in turn part of an older prehistoric landslide, less than about 6,000 years old, on the steep slope directly above La Conchita. As we shall see this 6,000 year old slide is part of an even older, larger prehistoric slide on the mountain above.

The winter of 2004-2005 was particularly wet, with high-intensity rainfall occurring at times. Neither residents nor local officials recognized that another landslide was imminent. The 2005 debris flow was different from that of 1995 in that the flow was faster, at 45 km/hr (30 mph), and moved further into the community. A number of people were trapped in their homes while others ran for their lives.

Directly behind the community is a 200 m (600 ft) high slope that produces continuing landslide hazards for humans living below it. La Conchita should never have been constructed at the foot of that slope. It has been known that landslides have occurred in the area for about 100 years. More telling, the community is built on about 15 m (50 ft) of old landslide deposits. Landslides above La Conchita and to the east and west have been occurring for thousands of years, long before people made the decision to build beach homes at the base of the steep slope.

A study of La Conchita and the surrounding area suggests that the debris flows and slides of 1995,2005, and older events are a part of a much larger prehistoric landslide less than about 40,000 years old that had not been recognized at the time of the more recent events (Figure 9.1). There is no evidence that the much larger, older prehistoric slide is moving as a mass, but parts are active, especially at the western margin of the slide.[1]

It is not *if*, but *when* future landslides will occur on the slopes above La Conchita. No part of the La Conchita community exempt from a future landslide.[2]

A potential solution to reduce the hazard to people and houses is to transform the land use of La Conchita from an area where people live to a coastal park. Not all people living there will be happy to hear such a suggestion, but society could help relocate people with fair compensation for valuable coastal property. The result would be a transformation of a hazardous site into a resource for future generations. At the least, we need to be diligent in the future concerning land-use planning and avoid unwise development on the large prehistoric slide above La Conchita. A similar, but smaller, prehistoric slide was reactivated in Malibu, California, in the mid-1980s, causing claimed damages in excess of $200 million.

What has been learned so far at La Conchita is that both prehistoric and active landslides can be recognized and their future activity evaluated. We now need to be proactive and take steps to reduce risk from future landslides.

9.1 Introduction to Landslides

Landslides and related phenomena cause substantial damage (Figure 9.2) and loss of life. In the United States, between 25 and 50 people are killed each year by landslides. This number increases to between 100 and 150 if collapses of trenches and other excavations are included. The total annual cost of damages is about $3.5 billion.[3]

Landslides and other types of ground failure are natural phenomena that would occur with or without human activity. However, human land use has led to an increase in these events in some situations and a decrease in others. For example, landslides may occur on previously stable hillsides that have been modified for housing development; on the other hand, landslides on naturally sensitive slopes are sometimes averted through the use of stabilizing structures or techniques.

Mast wasting is a comprehensive term for any type of downslope movement of Earth materials. In its more restricted sense, mass wasting refers to a down-slope movement o
For the sake of convenience, we sometimes refer to all of these landslides. We will also discuss subsidence, a type of ground failure characterized by nearly vertical deformation, or the dawnward sinking of Earth materials. Subsidence often produces circular surface pits but may produce linear or irregular patterns of failure.

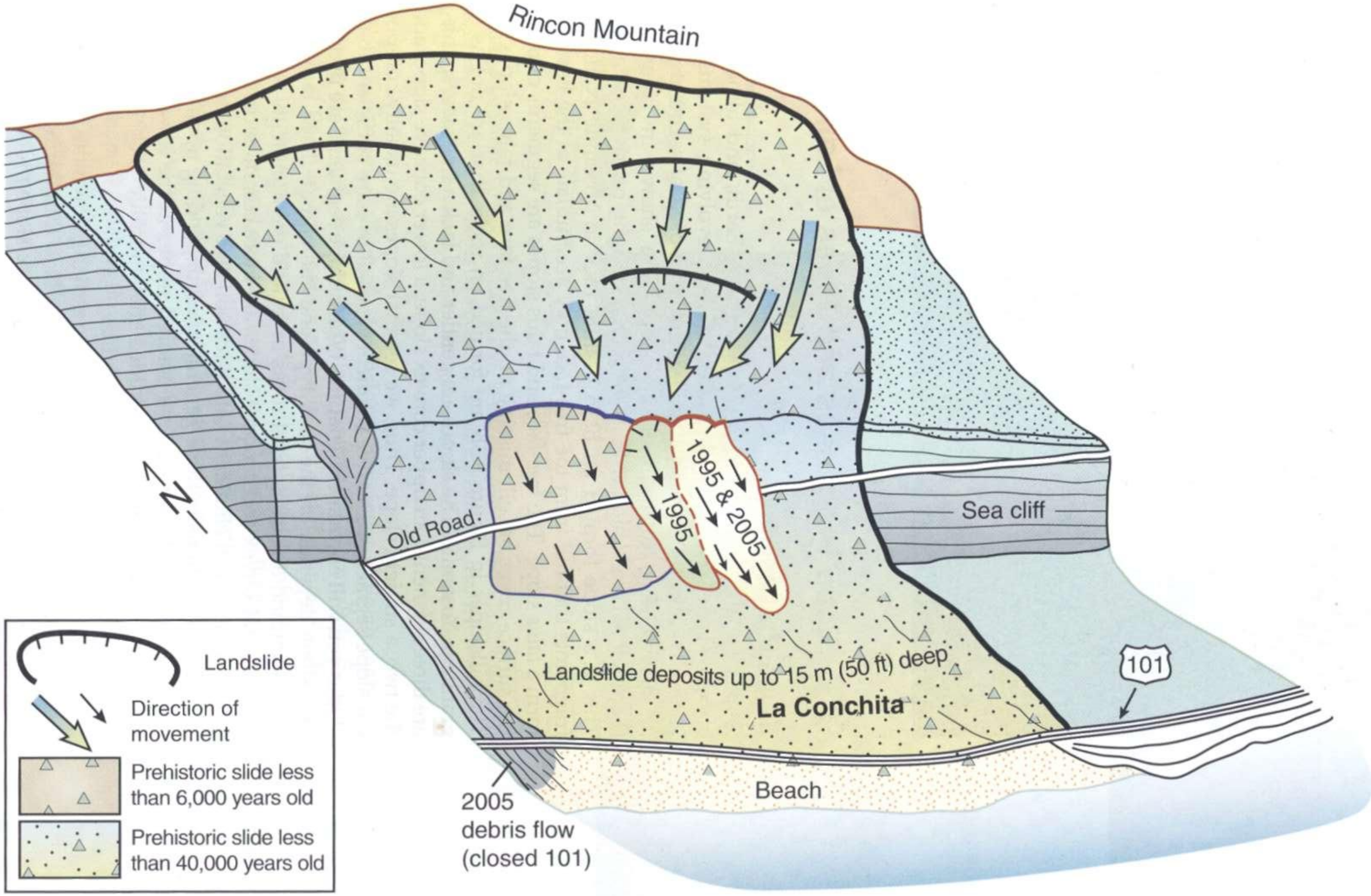


Figure 9.1 **Idealized diagram of landslides at La Conchita, CA** The fast-moving landslides of 1995 and 2005 are a reactivation of part of a larger prehistoric slide that is less than 6,000 years old, which is part of a much larger, older (few tens of thousands of years) landslide called the Rincon Mountain landslide.

Figure 9.2 Homes destroyed Aerial photograph of the lower part of the Portuguese Bend landslide in southern California (1950s). Note the kink in the pier near the end of the landslide. Eventually, most of the homes as well as the swim club and pier shown here were destroyed by the slow-moving landslide. *(John S. Shelton)*

9.2 Slope Processes and Types of Landslides

Slope Processes

Slopes are the most common landforms on Earth, and although most slopes appear stable and static, they are dynamic, evolving systems. Slopes are not generally uniform in their shape but are composed of segments that are straight or curved. Two different-looking slopes are shown in Figure 9.3. The first (Figure 9.3a) has a high cliff, or *free face,* a straight, nearly vertical slope segment. This is a slope formed on hard granite rock in Yosemite National Park. Rock fragments that fall from the free-face may accumulate at the base of the slope to form a *talus* slope. The free-face and talus slopes are segments of the slope. Notice the surface cover of soil, missing on the free face and talus slopes of Figure 9.3a. The hillslopes in Figure 9.3b are formed on rocks that are not as strong as the granite in Yosemite. The slopes are gentler and lack a free face. In this photo, there are three segments: an upper convex slope, a lower concave slope, and, separating the two, a straight slope. Thus, we see that slopes are usually composed of different slope segments. The five segment types above are sufficient to describe most slopes you will encounter in nature. Which slope segments are present on a particular slope depends on the rock type and the climate. Free-face development is more common on strong hard rocks or in arid environments where there is little vegetation. Convex and concave slopes are more common on softer rocks or with a more humid wet climate where thick soil and vegetation are present. But there are many exceptions to these general rules, depending upon local conditions. For example, the gentle, convex, red-colored slopes in the lower part of Figure 9.3b have formed on weak, easily eroded metamorphic rock (schist) in a semiarid climate on Santa Cruz Island, California.

Material on most slopes is constantly moving down the slope at rates that vary from an imperceptible creep of soil and rock to thundering avalanches and rockfalls that move at tremendous velocities. These slope processes are one significant reason that valleys are much wider than the streams they contain.

Types of Landslides

Earth materials may fail and move or deform in several ways (Figure 9.4). Rotational slumps involve sliding along a curved slip plain producing slump blocks

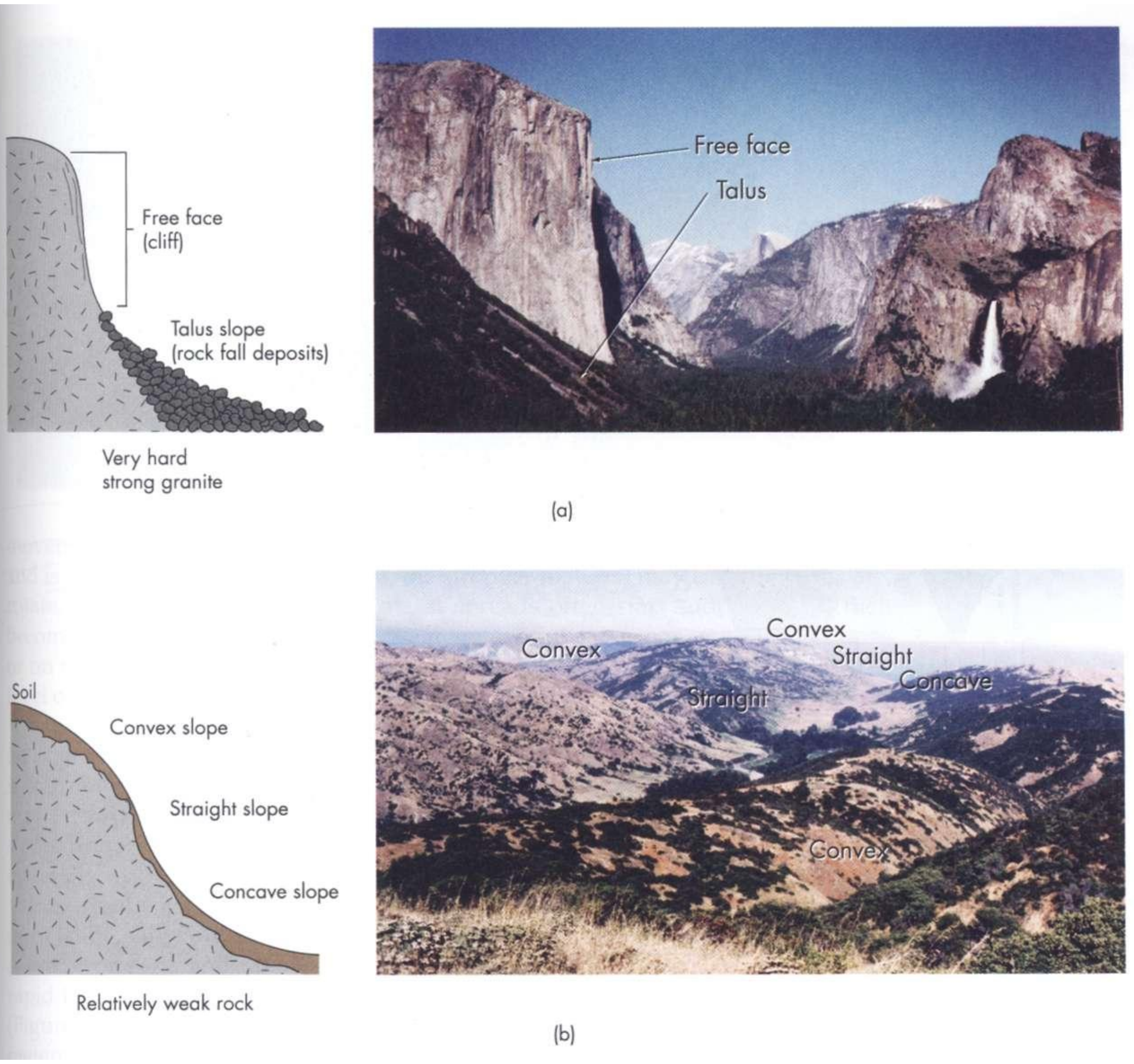
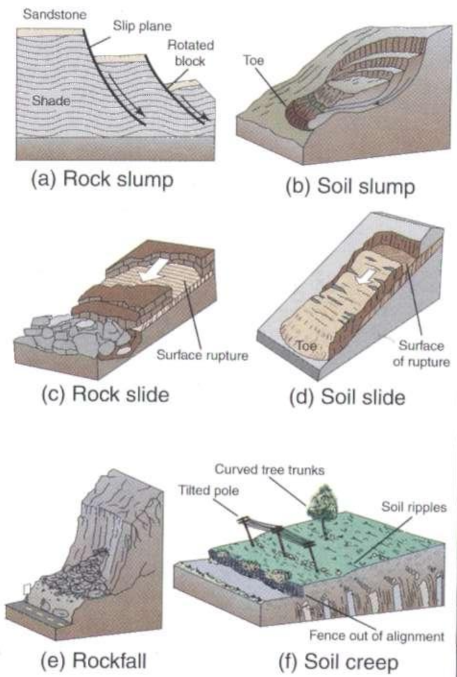


Figure 9.3 Slope segments (a) Slope on hard granite inYosemite National Park with free face (several thousand feet high) and talus slope, (b) Slopes on Santa Cruz Island, California, on relatively weak schist (red) and volcanic rocks (white), with convex, straight, and concave slope segments. *(Edward A. Keller)*

(Figure 9.4a, b). Translational sliding is downslope movement of Earth materials along a planar slip plane such as a bedding plane or fracture (Figure 9.4c, d). Rock fall is the free fall of Earth materials from a free face of a cliff (Figure 9.4e). Flows are the downslope movement of unconsolidated (usually saturated) materials in which particles move about and mix within the mass. Very slow flowage of rock or soil is called creep (Figure 9.4f); rapid flowage may be an earthflow, mudflow, or debris flow. An earthflow (Figures 9.4g and 9.5) often originates on a slope where soil partially liquefies and runs out. The source area becomes a bowl-shaped depression and a depositional area spreads out at the toe of the slope, giving the event an "hourglass shape." A debris flow or mudflow (Figure 9.4h) is a mixture of rock, soil, and organic matter that mixes with air and water to flow rapidly down slope. The upper part of the flow is often confined to a channel or valley but may spread out when it is no longer confined. A debris flow has less than 50 percent fines (sand, silt, and clay), whereas a mudflow has more than 50 percent fines by volume. A debris avalanche (Figure 9.4i) is a very rapid to extremely rapid debris flow. Large debris avalanches can cause catastrophic damage and loss of life. Lateral spreads (Figure 9.4j) are a type of landslide that often occurs on nearly flat slopes or very gentle slopes. The movement starts with liquefaction of silts, clays, or fine sands during earthquake shaking or other disturbance. The actual



Type of Movement	Materials	
	Rock	Soil
Landslides with variable water content and rate of movement	Rotational	
	Slump(a)	Slump(b)
	Translational	
	Rock slide(c)	Soil slide (slip)(d)
Falls	Rock fall(e)	Soil fall
Flows: Slow	Rock creep	Soil creep(f)
↓	Unconsolidated rock and soil (saturated)	
Rapid	Earth flow(g)	
↓	Debris flow / mud flow(h)	
Very rapid	Debris avalanche(i)	
Lateral spread	Rock(j)	Soil
Subsidence	Rock(k)	Soil
Complex	Combination of slides, slumps, and flows(l)	

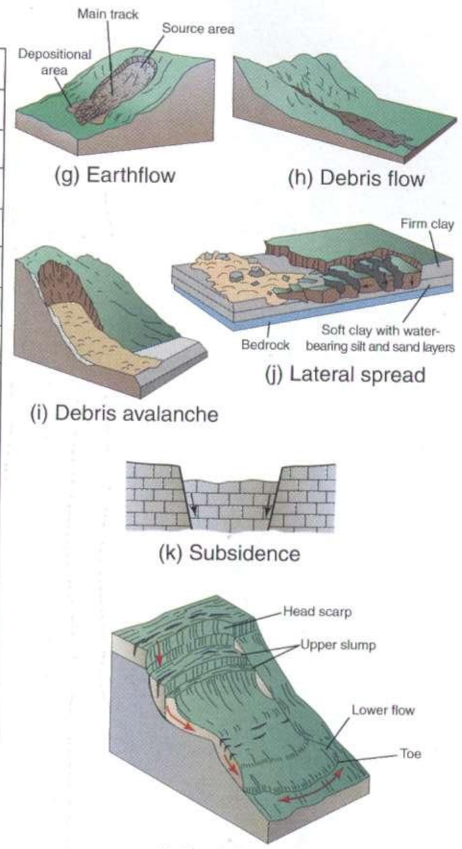


Figure 9.4 **Types of landslides** Classification of landslides based on type of movement, materials, water content, and rate of movement. *(Modified after U.S. Geological Survey 2004. Fact Sheet 2004-3072)*

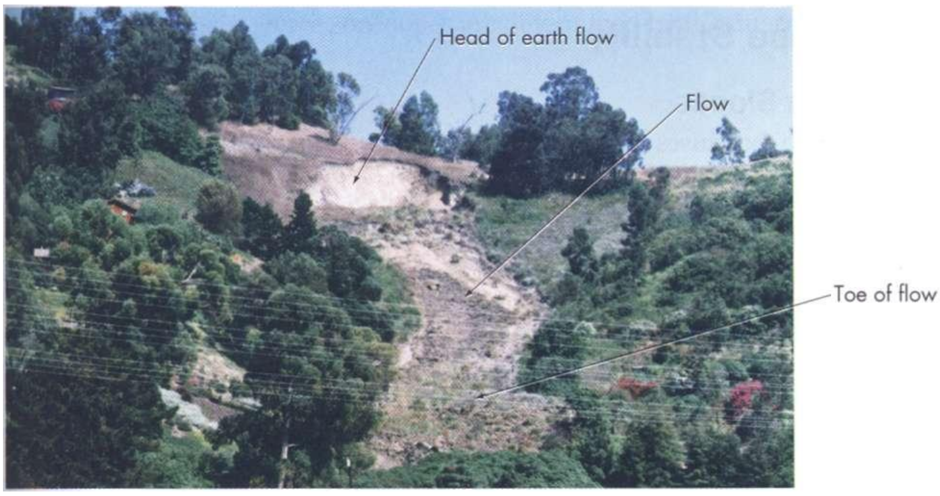


Figure 9.5 Earthflow on soft shale near Santa Barbara, California. *(Edward A. Keller)*

movement is lateral extension. If stronger coherent rock or soil is at the surface and is over a soil layer that liquefies, the stronger material may fracture, translate, rotate, or disintegrate and flow. Lateral spreads often start suddenly and then become larger in a slower, progressive manner.[3] Subsidence may occur on slopes or on flat ground and involves the sinking of a mass of Earth material below the level of the surrounding surface (Figure 9.4k).

Landslides are commonly complex combinations of sliding and flowage. As an example, Figures 9.41 and 9.6 show failures consisting of an upper *slump* that is transformed to a flow in the lower part of the slide. Such complex landslides may form when water-saturated Earth materials flow from the lower part of the slope, undermining the upper part and causing slumping of blocks of Earth materials.

Important variables in classifying downslope movements are the type of movement (slide, fall, flow, slump, or complex movement), slope material type, amount of water present, and rate of movement. In general, the movement is considered rapid if it can be discerned with the naked eye; otherwise, it is classified as slow (Figure 9.4). Actual rates vary from a slow creep of a few millimeters or centimeters per year to very rapid, at 1.5 m (5 ft) per day, to extremely rapid, at 30 m (98 ft) or more per second.[4]

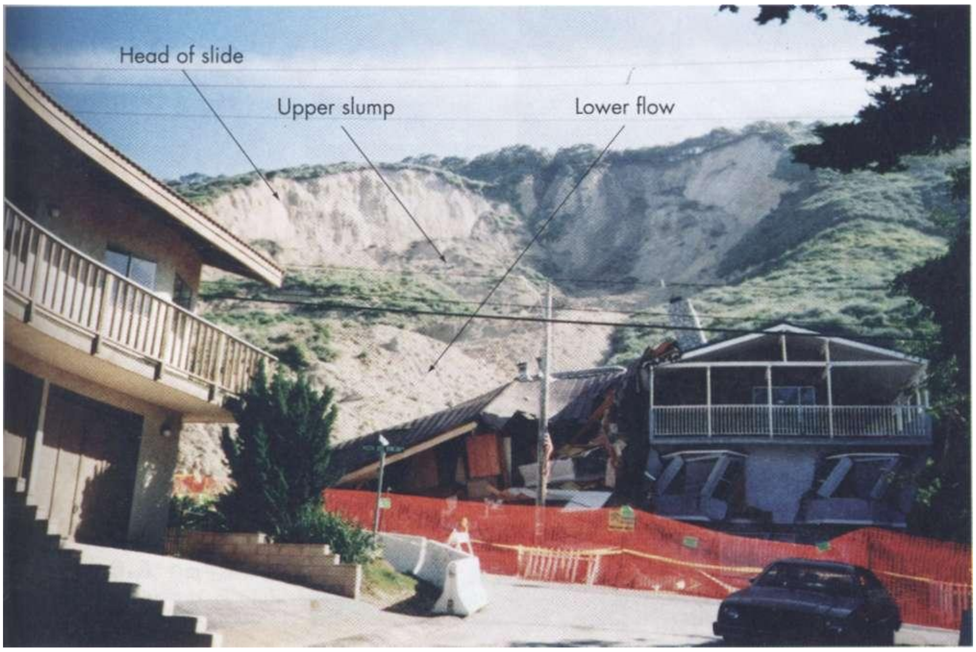


Figure 9.6 Complex landslide at La Conchita, California (1995). This slide, which had an upper slump block and a lower flow, destroyed the three-story home in its path. *(Edward A. Keller)*

9.3 Slope Stability

Forces on Slopes

To determine the causes of landslides, we must examine slope stability, which can be expressed in terms of the forces that act on slopes. The stability of a slope expresses the relationship between *driving forces,* which move Earth materials down a slope, and *resisting forces,* which oppose such movement. The most common driving force is the downslope component of the weight of the slope material, including anything superimposed on the slope such as vegetation, fill material, or buildings. The most common resisting force is the strength, or the resistance to failure by sliding or flowing, of the slope material acting along potential slip planes. Potential *slip planes* are geologic surfaces of weakness in the slope material; for example, foliation planes in a slope composed of schist, bedding planes in sedimentary rocks, and fractures in all rock types are potential slip planes.

Slope stability is evaluated by computing a safety factor (SF). defined as the ratio of the resisting forces to the driving forces. If the safety factor is greater than 1, the resisting forces ex
failure can be expected. Driving and resisting forces are not static: As local conditions change, these forces may change, increasing or decreasing the safety factor.

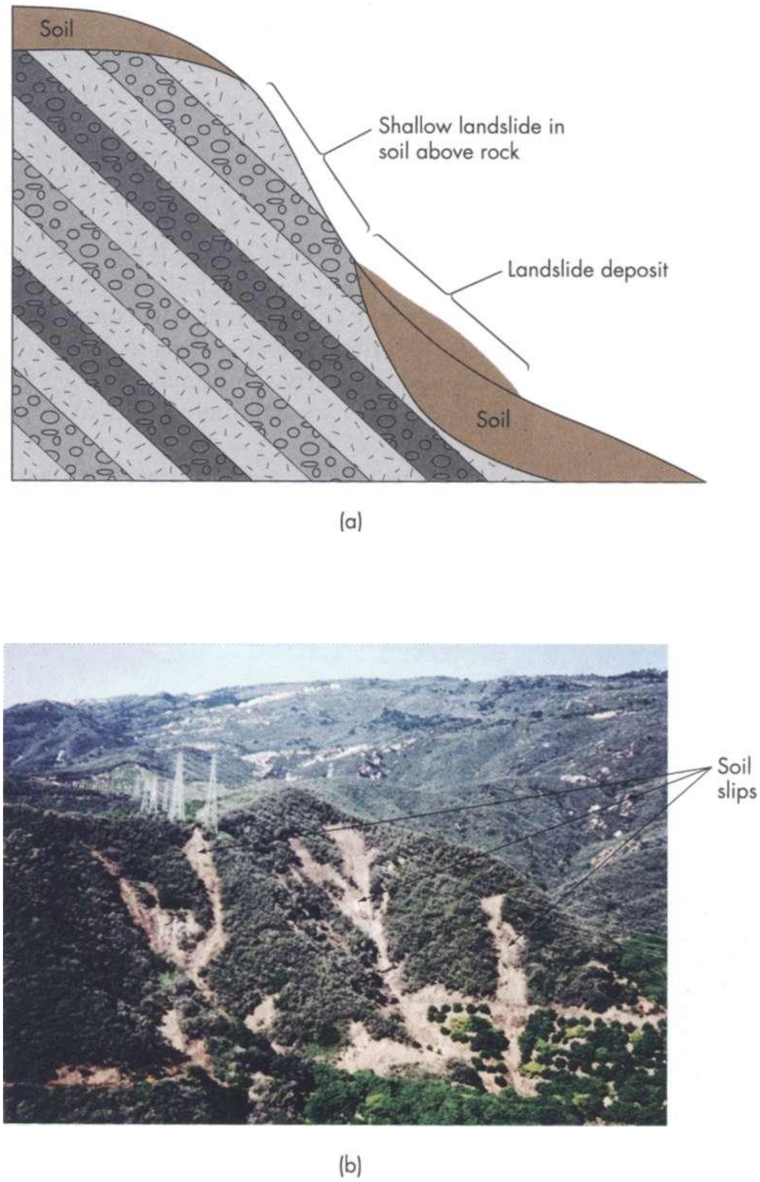


Figure 9.7 **Multiple soil slips**
(a) Diagram of a shallow soil slip.
(b) Shallow soil slips on steep slopes in southern California. The vegetation is low brush known as chaparral.
(Edward A. Keller)

Driving and resisting forces on slopes are determined by the interrelationships of the following variables:

- Type of Earth materials
- Slope angle and topography
- Climate
- Vegetation
- Water
- Time

The Role of Earth Material Type

The material composing a slope affects both the type and the frequency of downslope movement. Slides have two basic patterns of movement, rotational and translational. In **rotational slides,** or slumps, the sliding occurs along a curved slip surface (Figure 9.4a, b). Because the movement follows a curve, slump blocks, the blocks of Earth material that are undergoing slump, tend to produce topographic benches, which can be rotated and tilted in the upslope direction like those in Figure 9.4b. Slumps are most common on soil slopes, but they also occur on some rock slopes, most often in weak rock such as shale. **Translational slides** are planar; that is, they occur along inclined slip planes within a slope (Figure 9.4c, d) (see A Closer Look: Translation Slides Along Bedding Planes). Common translation slip planes in rock slopes include fractures in all rock types, bedding planes, weak clay layers, and foliation planes in metamorphic rocks. *Soil slips,* another type of translational slide, can also occur in some areas. Soil slips are very shallow slides in soil over rock that occur parallel to the slope (Figure 9.7). For soil slips,

^CLOSER LOOK Translation Slides Along Bedding Planes

Bedding planes are potential slip planes for landslides when they are inclined downslope and "daylight"—that is, are exposed on the surface of a slope. A slope of a seacliff with daylighting bedding planes in shale is diagramatically shown on Figure 9.A. Several months later in 2003 the slope failed, perhaps as a result of water added to the top of the slope where grass was planted and watered. The landslide deposits cover part of the sandy beach (Figure 9.B) and a catastrophe was narrowly avoided as a beach party was happening a short distance away.

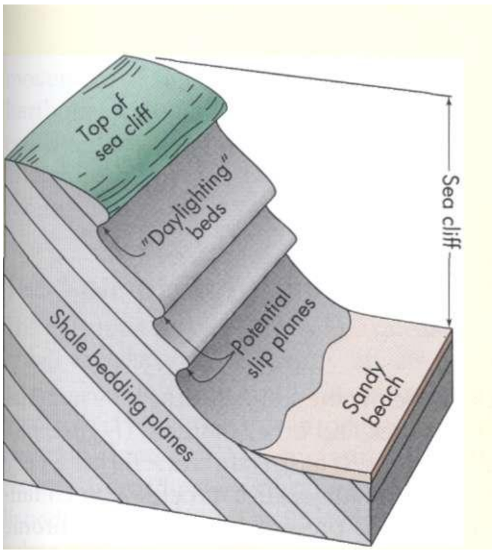


Figure 9.A Daylighting beds Bedding planes that intersect the surface of the land on a slope are said to"daylight."Such beds are potential slip planes.

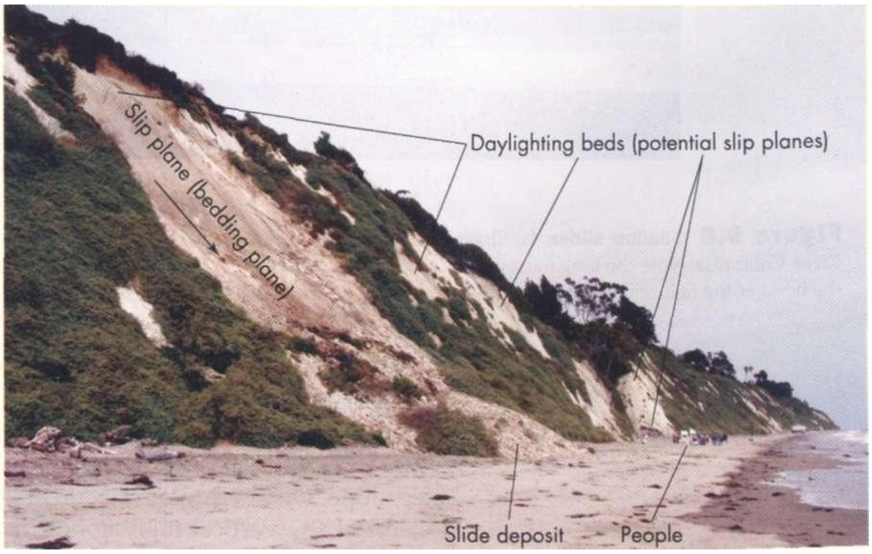
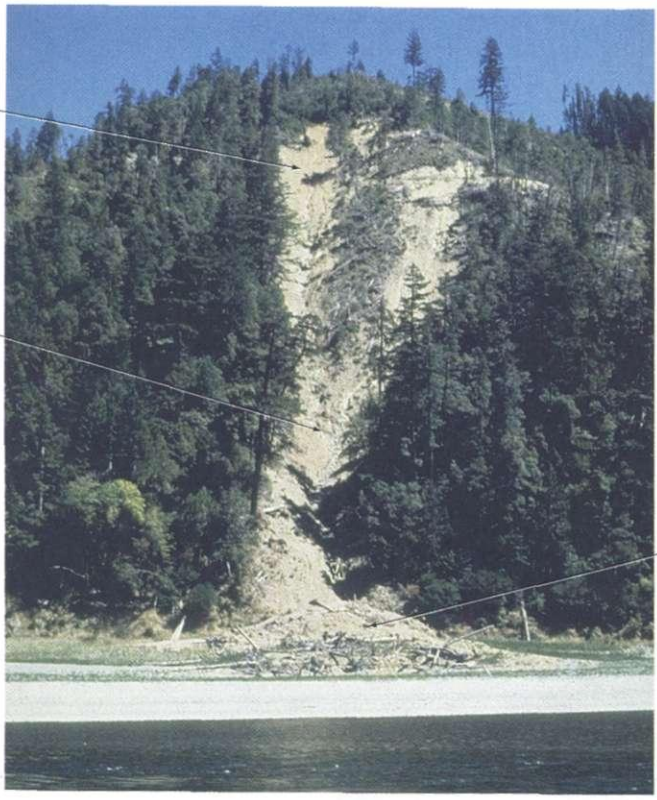


Figure 9.B Translation slide This slide occurred in late 2003. Failure was along a"daylight"bedding plane. Slide deposits cover part of the beach. *(Edward A. Keller)*

(a)



(b)

Figure 9.8 **Shallow** slides (a) Shallow soil slip, North Carolina, (b) Shallow debris flow, Klamath River, California. Note the long narrow track and debris on the bank of the river. The logging road near the bend of the failure may have helped destabilize the slope. *(Edward A. Keller)*

the slip plane is usually above the bedrock but below the soil within a slope material known as colluvium, a mixture of weathered rock and other material (Figure 9.8).

Material type is a factor in falls as well as slides. If a resistant rock forms a very steep slope, weathering or erosion along fractures may cause a rockfall. Such failures on nearly vertical high slopes in hard granite present a continuous, chronic hazard in Yosemite National Park (Figure 9.9).

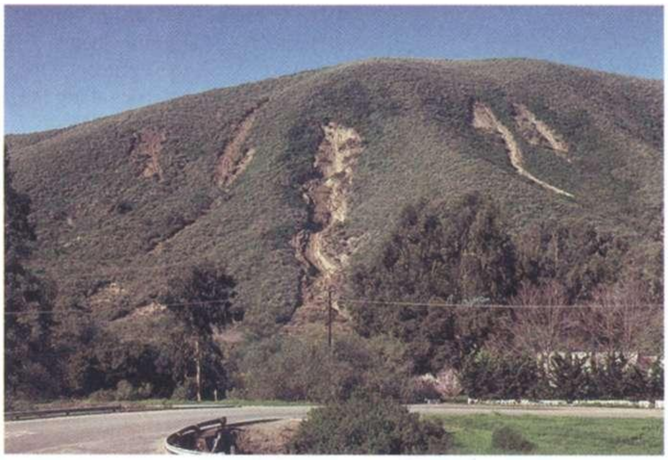
The type of materials composing a slope may greatly influence the type of slope failure that occurs. For example, on shale slopes or slopes on weak volcanic pyroclastic materials, failure commonly occurs as *creep*, the very slow downslope

Figure 9.9 Rockfall, Yosemite National Park, California This rockfall occurred at 6:52 pm, on July 10,1996 at Happy Isles along the Merced River. The rockfall fell from near Glacer Point 665 m (2,180 ft) to the valley floor, reaching a speed or 110 m/s (250 mph). One person was killed and over 1,000 trees were blown down by the blast of air. The volume of rock was about 30,000 m^3. If the fall had occurred earlier when numerous people were at the Happy Isles Visitors Center, many deaths could have resulted. *(Edwin L. Harp/U.S. Geological Survey/U.S. Department of the Interior)*

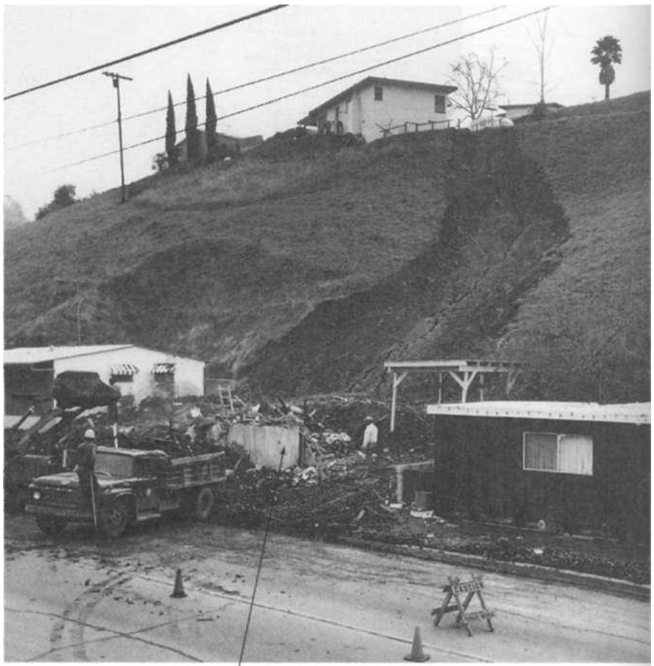
movement of soil or rock; *earthflozvs,* or mudflows, the downslope flow of saturated Earth materials; slumps; or soil slips. Slopes formed in resistant rock such as well-cemented sandstone, limestone, or granite do not experience the same problems. Therefore, before developing on shale or other weak rock slopes, people must give careful consideration to the potential landslide hazard.

The Role of Slope and Topography

The hillslope angle, which is a measure of how steep a hillslope is, is usually called the *slope.* Slope greatly affects the relative magnitude of driving forces on slopes. As the slope of a hillside or potential slip plane within a slope increases, say from 15 degrees to 45 degrees or steeper, the driving force also increases; therefore, landslides are more frequent on steep slopes. A study of landslides that occurred during two rainy seasons in California's San Francisco Bay area established that 75 percent to 85 percent of landslide activity is closely associated with urban areas on steep slopes.[5] Within the United States, the coastal mountains of California and Oregon, the Rocky Mountains, and the Appalachian Mountains have the greatest frequency of landslides. All of the types of downslope movement shown on Figure 9.4 occur on steep slopes in those locations.



(a)



(b)

House destroyed

Figure 9.10 Shallow soil slips can kill (a) Shallow soil slips on steep southern California, vegetated slopes. *(Edward A. Keller)* (b) A home in southern California destroyed by a shallow soil slip, debris flow that originated as a soil slip. This 1969 event claimed two lives. (Courtesy *of John Shadle, Los Angeles Department of Building and Safety)*

Steep slopes are often associated with rockfalls and *debris avalanches,* which are the very rapid downslope movement of soil, rock, and organic debris. In southern California, shallow soil slips are common on steep saturated slopes. Once they move downslope, these soil slips are often transformed into earthflows or debris flows, which can be extremely hazardous (Figure 9.10). Earthflows can occur on moderate slopes, and creep can be observed on very gentle slopes.

Debris flows are the downslope flow of relatively coarse material; more than 50 percent of particles in a debris flow are coarser than sand. Debris flows can move very slowly or rapidly, depending on conditions. Debris flows, debris avalanches, and mudflows vary in size: they can be relatively small to moderate events, confined to a single valley of slope with a few hundred to hundreds of thousands of cubic meters of debris. However, they can also be huge events involving an entire flank of a mountain, measured in cubic kilometers of material (see volcanic mudflows and debris flows, discussed in Chapter 7).

The Role of Climate

Climate can be defined as characteristic weather at a particular place or region over seasons, years, or decades. Climate is more than the average air temperature and amount of precipitation. Climate includes seasonal patterns of weather such as winter rains along the West Coast of the United States, summer thunderstorm activity in the southwestern United States, and hurricane activity of the southeastern United States. The subject of climate and how it changes is discussed in detail in Chapter 19.

The role of climate is important in our discussion of landslides because climate influences the amount and timing of water, in the form or rain and snow, that may infiltrate or erode a hillslope as well as the type and abundance of vegetation that grows on a hillslope. Hillslopes in arid and semiarid climates tend to have sparse vegetation and soils with a lot of bare rock exposed. Slope elements such as the free-face and talus slopes tend to be more common because small differences in resistance of rock to weathering and erosion are emphasized. Common landslide activity in arid and semiarid regions includes rockfall, debris flows, and shallow soil slips.

The Role of Vegetation

In the more subhumid to humid regions of the world, vegetation is abundant, thick soil cover develops, and the slopes have many more convex and concave slope segments. Landslide activity includes deep complex landslides, earthflows, and soil creep. The role of vegetation in landslides and related phenomena is complex. Vegetation in an area is a function of several factors, including climate, soil type, topography, and fire history each of which also influences what happens on slopes. Vegetation is a significant factor in slope stability for three reasons:

- Vegetation provides a cover that cushions the impact of rain falling on slopes, facilitating infiltration of water into the slope while retarding grain-by-grafn erosion on the surface.
- Vegetation has root systems that tend to provide an apparent cohesion (like iron bars in concrete) to the slope materials, which increases resistance to landsliding.
- Vegetation adds weight to the slope.

In some cases, the presence of vegetation increases the probability of a landslide, especially for shallow soil slips on steep slopes. In southern California coastal areas, one type of soil slip occurs on steep-cut slopes covered with low vegetation called ice plant (Figure 9.11). During especially wet winter months, the shallow-rooted ice plants take up water, adding considerable weight to steep slopes—each leaf stores water and looks like a small canteen—thereby increasing the driving forces. The plants also cause an increase in the infiltration of water into the slope, which decreases the resisting forces. When failure occurs, the plants and several centimeters of roots and soil slide to the base of the slope.

Soil slips on natural steep slopes are a serious problem in southern California. Chaparral, the dense shrubs or brush shown in Figure 9.7, facilitates an increase in water infiltrating into the slope, lowering the safety factor.[6]

The Role of Water

Water is almost always directly or indirectly involved with landslides, so its role is particularly important.[7] When studying a landslide, we look first to examine what the water on or in the slope is doing. There are three basic ways in which water

Figure 9.11 Ice plants on slopes are often unstable Shallow soil slips on steep slopes covered with shallow-rooted ice plants near Santa Barbara, California: (a) an embankment on a road; (b) a home site. The plastic sheet is an attempt to reduce infiltration of rain water. *(Edward A. Keller)*

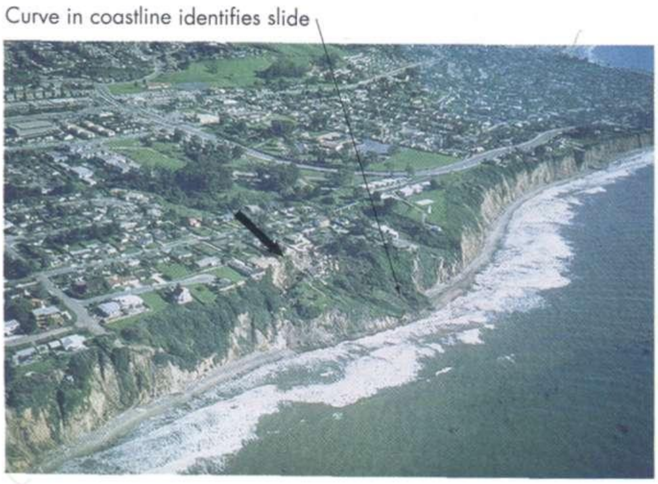
(a)

(b)

Figure 9.12 Water eroding the toe of a slope causes instability (a) Stream-bank erosion caused this failure, which damaged a road, San Gabriel Mountains, California. *(Edward A. Keller)* (b) Beachfront home being threatened by a landslide, Cove Beach, Oregon. *(Gary Braasch/Getty Images Inc.)*

on or in the slope can affect stability: (1) landslides such as shallow soil slips can develop during rainstorms when slopes become saturated; (2) landslides such as slumps or translational slides can develop months or even years after infiltration of water deep into the slope; and (3) water can erode the base or toe of a slope, thereby decreasing slope stability.

Water's ability to erode affects the stability of slopes. Stream or wave erosion on a slope may remove material and create a steeper slope, thus reducing the safety factor (Figure 9.12). This problem is particularly critical if the base of the slope is an old, inactive landslide that is likely to move again if stability is reduced (Figure 9.13). Therefore, it is important to recognize old landslides along potential



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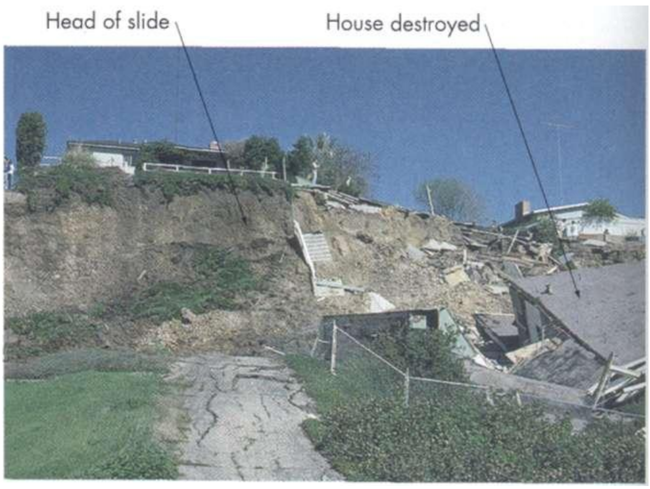


(b)

Figure 9.13 Reactivation of a slide (a) Aerial view of a landslide along the Santa Barbara coastal area. The arrow points to the location of the slide, (b) Closeup of the slide, which destroyed two homes. The slide is a reactivation of an older failure. *(Courtesy of Don Weaver)* road cuts and other excavations before construction in order to isolate and correct potential problems.

Another way that water can cause landslides is by contributing to spontaneous liquefaction of clay-rich sediment, or *quick clay*. When disturbed, some clays lose their shear strength, behave as a liquid, and flow. The shaking of clay below Anchorage, Alaska, during the 1964 earthquake produced this effect and was extremely destructive. In Quebec, Canada, several large slides associated with quick clays have destroyed numerous homes and killed about 70 people. The slides occurred on river valley slopes when initially solid material was converted into a liquid mud as the sliding movement began.[8] These slides are especially interesting because the liquefaction of clays occurs without earthquake shaking. The slides are often initiated by river erosion at the toe of the slope and, although they start in a small area, may develop into large events. Since they often involve the reactivation of an older slide, future problems may be avoided by restricting development in these areas.

The Role of Time

The forces on slopes often change with time. For example, both driving and resisting forces may change seasonally as the moisture content or water table position alters. Much of the chemical weathering of rocks, which slowly reduces their strength, is caused by the chemical action of water in contact with soil and rock near Earth's surface. Water (H_2O) is often acidic because it reacts with carbon dioxide (CO_2) in the atmosphere and soil to produce weak carbonic acid (H_2CO_3) This chemical weathering is especially significant in areas with limestone, which is susceptible to weathering and decomposition by carbonic acid. Changes due to weathering are greater in especially wet years, as reflected by the increased frequency of landslides during or after wet years. In other slopes, there may be a continuous reduction in resisting forces over time, perhaps due either to weathering, which reduces the cohesion in slope materials, or to a regular increase in pore water pressure in the slope from natural or artificial conditions. A slope that is becoming less stable with time may have an increasing rate of creep until failure occurs. The case history of the Vaiont Dam illustrates this concept (see Case History: Vaiont Dam).

CASE HISTORY Vaiont Dam

The world's worst dam disaster occurred on October 9, 1963, when approximately 2,600 lives were lost at the Vaiont Dam in Italy (Figure 9.C). The disaster involved the world's highest thin-arch dam, yet, strangely, no damage was sustained by the main shell of the dam or the abutments.[9] The tragedy was caused by a huge landslide in which more than 238 million cubic meters (0.06 mi^3) of rock and other debris moved at speeds of about 95 km per hour (59 mi per hour) down the north face of the mountain above the reservoir. Slide material completely filled the reservoir for 1.8 km (1.1 mi.) along the axis of the valley to heights of nearly 152 m (500 ft) above the reservoir level. The rapid movement created a tremendous updraft of air and propelled rocks and water up the north side of the valley, higher than 250 m (820 ft) above the reservoir level. The slide and its accompanying blasts of air, water, and rock produced strong earthquakes recorded many kilometers away. It blew the roof off one man's house well over 250 m (820 ft) above the reservoir and pelted the man with rocks and debris. The filling of the reservoir produced waves of water more than 90 m (295 ft) high that swept over the abutments of the dam. The waves were still more than 70 m (230 ft) high more than 1.5 km (0.9 mi) downstream; in fact, everything for many kilometers downstream was completely destroyed. The entire event—slide and flood—was over in less than 7 minutes.

The landslide followed a 3 year period of monitoring the rate of creep on the slope, which varied from less than 1 to as many as 30 cm (12 in.) per week, until September 1963, when it increased to 25 cm (10 in.) per day. Finally, on the day before the slide, it was about 100 cm (39 in.) per day. Although engineers expected a landslide, they did not realize until the day before the slide that a large area was moving as a uniform, unstable mass. Interestingly, animals grazing on the slope had sensed danger and moved away on October 1, over a week before the landslide.

The slide was caused by a combination of factors. First, adverse geologic conditions—including weak rocks and limestone with open fractures, sinkholes, and weak clay layers that were inclined toward the reservoir—produced unstable blocks (Figure 9.D). Second, very steep topography created a strong driving force. Third, water pressure was increased in

Soils and Environment

Learning Objectives

Soils are an important part of our environment. Virtually all aspects of the terrestrial environment interact with soils at some level. For example, we depend upon fertile soil to grow our food, and soil properties determine, in part, the suitability of land for uses such as construction and waste disposal. As a result, the protection of soil resources is an important objective. With this in mind, we will focus on the following learning objectives for this chapter:

- Understand soil terminology and the processes responsible for the development of soils
- Understand soil fertility and the interactions of water in soil processes
- Become familiar with soil classification
- Understand the primary engineering properties of soils
- Understand relationships between land use and soils
- Know what sediment pollution is and how it can be minimized
- Understand how soils affect land-use planning
- Understand how we can sustain soil resources

Town abandoned when soil pollution is discovered The town of Times Beach, Missouri, in the 1980s became a ghost town: evacuated, abandoned, fenced off, and bulldozed following discovery of dioxin contamination. *(Tom McHugh/Photo Researchers, Inc.)*

CASE HISTORY Times Beach, Missouri

Times Beach, Missouri, population 2,400, was a river town located just west of St. Louis. In 1983 the town was evacuated and purchased for $36 million by the government; Times Beach became a ghost town when it was discovered that oil sprayed on the town's road to control dust contained dioxin (Figure 16.1). Dioxin is a colorless crystal composed of oxygen, hydrogen, carbon, and chlorine. It is known to be extremely toxic to mammals and is suspected of being a carcinogen in humans. There are approximately 75 types of dioxin, which is produced as a by-product during the production of organic chemicals such as herbicides.[1] Dioxin became a household word during and after the Vietnam War; it is a component of Agent Orange, the name given to herbicides that were used to defoliate large areas in the war zones. Military personnel as well as civilians were exposed to Agent Orange and the dioxin within it. Lawsuit settlements pertaining to dioxin's role in causing diseases in people exposed to it compensated 250,000 Vietnam veterans and their families.

At Times Beach, Missouri along the Meramec River, 32 km (20 mi) southwest of St. Lewis, tests determined that the entire area had been contaminated with dioxin that had seeped into the soil from the oil applied to the roads. The decision was made in 1985 to evacuate the town and bulldoze the buildings. Following clean up and planting trees, the area today is a state park and bird refuge.

The effects of human exposure to dioxin is a controversial subject. Apparently, there is a cancer risk to workers who handle chemicals that contain dioxin, but it is not thought to be a widespread and significant cancer threat to people who are exposed to very low levels of the chemical.[2] Some scientists, including the person who ordered the evacuation, have since stated that the evacuation at Times Beach may have been an overreaction by the government to the perceived hazard of dioxin. Research concerning the potential hazard presented from exposure to dioxin continues, and the controversy concerning its potential harmful effects to people and ecosystems is still being debated.

(a) (b)

Figure 16.1 Dioxin pollutes soil in Missouri (a) Times Beach, Missouri, showing a deserted building after dioxin was found to be contaminating the area. *(Corbis/Sygma)* (b) Examination of soils contaminated by dioxin at Times Beach, Missouri. The town was evacuated because of the dioxin scare. *(0. Franken/Corbis/Sygma)*

16.1 Introduction to Soils

Soil may be defined in several ways. Soil scientists define soil as solid Earth material that has been altered by physical, chemical, and biological processes such that it can support rooted plant life. Engineers define soil as solid Earth material that can be removed without blasting. Both of these definitions are important in environmental geology. Geologists must be aware of the different definitions; they must also be aware of the research concerning both soil-producing processes and the role of soils in environmental problems. Engineers have developed the field of soil mechanics to quantify engineering properties of soils such as soil strength and moisture content.

The study of soil properties, particularly with reference to land-use limitations, is becoming an important aspect of environmental work in the following ways:

- In land-use planning, the suitability of land for a particular use, or *land capability,* is often determined in part by the soils present. Soil properties are especially important for uses such as urbanization, timber management, and agriculture.
- Soils are critical when we consider waste-disposal problems. Interactions between waste, water, soil, and rock often determine the suitability of a particular site to receive waste.
- The study of soils helps land-use planners evaluate natural hazards, including floods, landslides, and earthquakes. Floodplain soils differ from upland soils, and consideration of soil properties helps delineate natural floodplains. Evaluating the relative ages of soils on landslide deposits may provide an estimate of the frequency of slides; this information assists in planning to minimize their impact. Soil studies have also been a powerful tool in establishing the age of Earth materials deformed by faulting; this information leads to better estimation of earthquake recurrence intervals.
- Soils often carry a climatic signal, something that indicates what the past climate was like. For example, calcium carbonate accumulates in desert soils, and organic matter such as bits of plants accumulates in some tropical soils. These constituents of soils assist in understanding regional and global climate change. Soil studies also provide important data used to understand how biological and geologic processes were linked in the development of both soils and ecosystems during the past few million years.[3]

16.2 Soil Profiles

Soil development is a complex process. The rock and hydrologic cycles interact to produce weathered rock materials that are basic ingredients of soils. *Weathering* is the physical and chemical breakdown of rocks and the first step in soil development (see Chapter 3). Weathered rock is further modified into soil by the activity of soil organisms. This process forms residual or transported soil. Weathered material that remains essentially in place is modified t

bedock. The red soils of the Piedmont in the southeastern United States, formed on igneous and metamorphic rocks, are an example of residual soil. Eroded rock particles that are transported by water, wind, or glaciers and then modified in their new deposition location form **transported soil.** The fertile soils formed on glacial deposits in the Midwestern United States are transported soils.

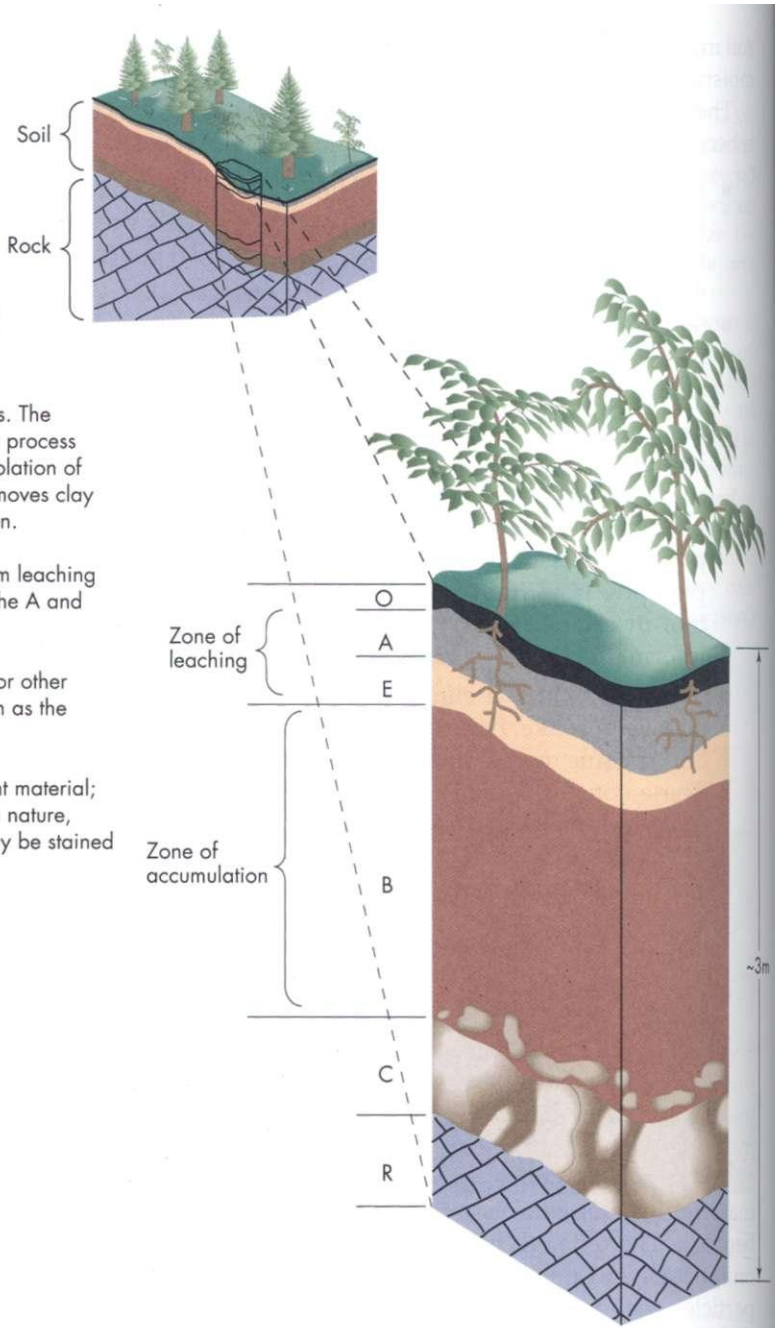
A soil can be considered an open system that interacts with other components of the geologic cycle. The characteristics of a particular soil are a function of climate, topography, parent material (the rock from which the soil is formed), maturity (age of the soil), and biological processes.

Soil Horizons

Vertical and horizontal movements of the materials in a soil system create a distinct layering, parallel to the surface, collectively called a **soil profile.** The layers are called zones or **soil horizons.** Our discussion of soil profiles mentions only the horizons most commonly found in soils. Additional information is available from detailed soils texts.[4,5,6]

Figure 16.2a shows the common master, or prominent, soil horizons. The 0 *horizon* and *A horizon* contain highly concentrated organic material such as

(a)



O. Horizon is composed mostly of organic materials including decomposed or decomposing leaves, twigs, etc. The color of the horizon is often dark brown or black.

A. Horizon is composed of both mineral and organic materials. The color is often light black to brown. Leaching, defined as the process of dissolving, washing, or draining Earth materials by percolation of groundwater or other liquids, occurs in the A horizon and moves clay and other material such as iron and calcium to the B horizon.

E. Horizon is composed of light-colored materials resulting from leaching of clay, calcium, magnesium, and iron to lower horizons. The A and E horizons together constitute the zone of leaching.

B. Horizon is enriched in clay, iron oxides, silica, carbonate, or other material leached from overlying horizons. Horizon is known as the zone of accumulation.

C. Horizon is composed of partially altered (weathered) parent material; rock is shown here but the material could also be alluvial in nature, such as river gravels in other environments. The horizon may be stained red with iron oxides.

R. Unweathered (unaltered) parent material.

(b)

Figure 16.2 Soil profiles (a) Idealized diagram showing a soil profile with soil horizons, (b) Soil profile showing a black A horizon, a light-red B horizon, a white K horizon rich in calcium carbonate, and a lighter C horizon. *(Edward A. Keller)*

decomposing plants. The differences between these two layers reflect the amount of organic material present in each. In general, the O horizon consists almost entirely of plant litter and other organic material, whereas the underlying A horizon contains a good deal of both organic and mineral material. Below the O or A horizon, some soils have an *E horizon; or zone* of leachin
that is leached of iron-bearing components. This horizon is light in color because it contains less organic material than the O and A horizons and little inorganic coloring material such as iron oxides.

The B horizon, or zone of accumulation, underles the O, A, or E horizons and consists of a variety of materials translocated downw

Environmental geologists are also interested in the *Bk* horizon, which is characterized by accumulation of calcium carbonate. The carbonate coats individual soil particles and may fill some pore spaces within the soil. It does not, however, dominate the structure of the horizon. If a soil horizon is impregnated with calcium carbonate to the extent that its morphology is dominated by the carbonate, it is designated a *K horizon* (Figure 16.2b). Carbonate completely fills the pore spaces in K horizons, often forming layers parallel to the surface. The term *caliche* is often used for an irregular accumulation or layers of calcium carbonate in Earth material near the surface.

The C horizon consists of parent material partially altered by weathering processes. It lies directly over the R horizon, which is u

The term *hardpan* is often used to refer to a hard compacted soil horizon, usually part of the B horizon. Hardpan is often composed of compacted clay or cemented with calcium carbonate, iron oxide, or silica. Hardpan horizons may be nearly impermeable and thus restrict the downward movement of soil water.

-3m

16.3 Soil Properties

Color

One of the first things we notice about a soil is its color, or the colors of its horizons. The O and A horizons tend to be dark because of their abundant organic material. The E horizon, if present, may be almost white because of the leaching of iron and aluminum oxides. The B horizon shows the most dramatic differences in color, varying from yellow-brown to light red-brown to dark red, depending on the presence of clay minerals and iron oxides. Bk horizons may be light-colored because of their carbonates, but they are sometimes reddish as a result of iron oxide accumulation. If a true K horizon has developed, it may be almost white because of the abundance of calcium carbonate. Although soil color can be an important diagnostic tool for analyzing a soil profile, one must be cautious about calling a red layer a B horizon. The original parent material, if rich in iron, may produce a very red soil even when there has been relatively little soil profile development.

Soil color may be an important indicator of how well a soil drains. Well-drained soils are well aerated, creating excellent oxidizing conditions; for example, in a well-aerated soil, iron produces soil with a red color. Poorly drained soils are wet, and these soils tend to have a yellow color. This distinction is important because

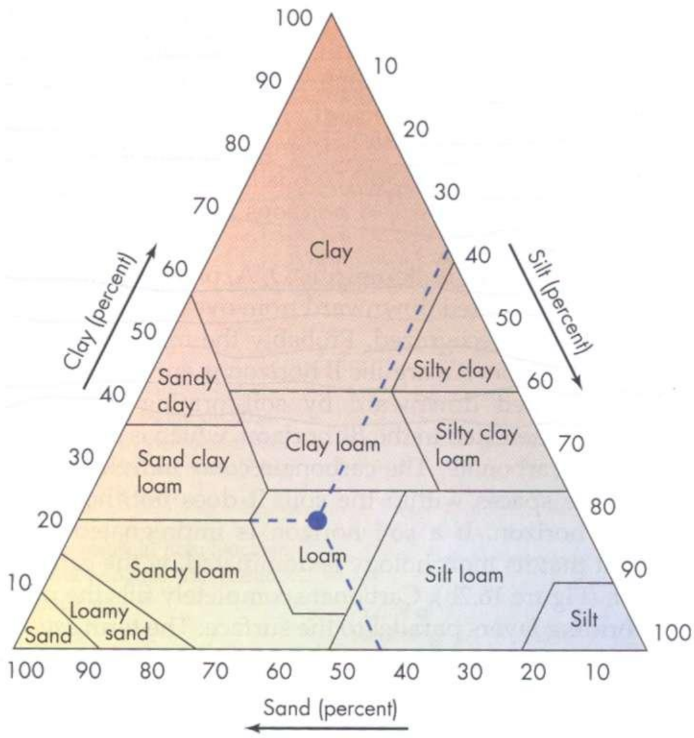


Figure 16.3 Soil texture classes The classes are defined according to the percentage of clay-, silt-, and sand-sized particles in the soil sample. The area defined by the point connected by dashed lines represents a soil composed of 40 percent sand, 40 percent silt, and 20 percent clay, which is classified as loam. *(From U.S. Department of Agriculture)*

poorly drained soils are associated with environmental problems, such as lower slope stability and an inability to be utilized as a disposal medium for household sewage systems.

Texture

The *texture* of a soil depends upon the relative proportions of sand-, silt-, and clay-sized particles (Figure 16.3). Clay particles have a diameter of less than 0.004 mm (0.0002 in.); silt particles have diameters ranging from 0.004 to 0.063 mm (0.0002 to 0.003 in.); and sand particles are 0.063 to 2.0 mm (0.003 to 0.08 in.) in diameter. Earth materials with particles larger than 2.0 mm (0.08 in.) in diameter are called gravel, cobbles, or boulders, depending on the particle size.

In the field, soil texture is commonly identified by estimation and then refined in the laboratory by separating and determining the proportions of the sand, silt, and clay. A useful field technique for estimating the size of sand-sized or smaller soil particles is as follows: It is sand if you can see individual grains, silt if you can see the grains with a 10 X hand lens, and clay if you cannot see grains with such a' hand lens. Another method is to feel the soil. Sand is gritty; it crunches between the teeth. Silt feels like baking flour, and clay is cohesive. When mixed with water, smeared on the back of the hand, and allowed to dry, clay cannot easily be dusted off, whereas silt or sand can.

Structure

Soil particles often cling together in aggregates called *peds* that are classified according to shape into several types. Figure 16.4 shows some of the common structures of peds found in soils. The type of structure present is related to soil-forming processes, but some of these processes are poorly understood.[4] For example, granular structure is fairly common in A horizons, whereas blocky and prismatic structures are most likely to be found in B horizons. Soil structure is an important diagnostic tool for evaluating the development and approximate age of soil profiles. In general, as the profile develops with time, structure becomes more complex and may go from granular to blocky to prismatic as the clay content in the argillic B horizons increases.

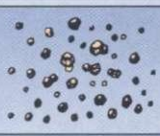
Types of peds	Typical size range	Horizon usually found in	Comments
Granular 	1–10 mm	*A*	Can also be found in *B* and *C* horizons
Blocky 	5–50 mm	B_t	Are usually designated as angular or subangular
Prismatic 	10–100 mm	B_t	If columns have rounded tops, structure is called columnar
Platy 	1–10 mm	*E*	May also occur in some *B* horizons

Figure 16.4 Soil structure Types and description of soil structure (peds).

16.4 Soil Fertility

A soil may be considered a complex ecosystem. A single cubic meter of soil may contain millions of living things, including small rodents, insects, worms, algae, fungi, and bacteria. These organisms are important for mixing and aerating the soil particles. They also help release or convert nutrients in soils into forms that are useful for plants.[7] Soil fertility refers to the capacity of the soils to supply nutrients, such as nitrogen, phosphorus, and potassium, needed for plant growth when other factors are favorable.[8]

Soils that developed on some floodplains and glacial deposits contain sufficient nutrients and organic material to be naturally fertile. Other soils, developed on highly leached bedrock or on loose deposits with little organic material, may be nutrient poor and have low fertility. Soils are often manipulated to increase plant yield by applying either fertilizers to supply nutrients or materials that improve the soil's texture and moisture retention. Soil fertility can be reduced by soil erosion or leaching that removes nutrients, by interruption of natural processes that supply nutrients, such as flooding, or by continued use of pesticides that alter or damage soil organisms.

The development and maintenance of many terrestrial ecosystems depend upon soil as a basic component of the system. Interactions between physical and biochemical processes operate over variable scales of time (hundreds to thousands of years) and space (from less than 1 km^2 to thousands of square kilometers) to produce soils that help support complex ecosystems. Soils go through stages of building, sustaining, and degrading.[3] Building is a relatively fast process that starts with a new substrate, or layer, such as sediment from a volcanic eruption or flood. Chemical weathering of minerals releases chemicals that can be used by a variety of organisms, including plants, that build soils. Sustaining soils involves longer time lines—thousands to several millions of years during which additional minerals in the soils continue to weather, forming clays. Soil degradation occurs as minerals necessary to support an ecosystem are depleted by a variety of near-surface physical, hydrologic, and biological processes. A physical process, soil erosion can remove upper soil horizons and their nutrients. In some cases, soil degradation processes may be reduced. For example, nutrients contained in dust from the deserts of Africa may reach islands of the Pacific, helping maintain soil fertility after weathering and water moving through the soil have removed some of the original mineral nutrients in soils.

16.5 Water in Soil

If you analyze a block of soil, you will find it is composed of bits of solid mineral and organic matter with pore spaces between them. The pore spaces are filled with gases, mostly air, or liquids, mostly water. If all the pore spaces in a block of soil are completely filled with water, the soil is said to be in a saturated condition; otherwise, it is said to be unsaturated. Soils in swampy areas may be saturated year-round, whereas soils in arid regions may be only occasionally saturated.[9]

The amount and movement of water through soils are important research topics. Both are linked to water pollution problems, such as the movement of gasoline from leaking underground tanks or the migration of liquid pollutants from waste-disposal sites.

16.6 Soil Classification

Terminology and classification of soils pose unique problems in environmental geology. We are often interested in both soil processes and human use of soil. A classification system, or *taxonomy,* that includes engineering as well as physical and chemical properties would be most appropriate, but none exists. We must therefore be familiar with two separate systems of soil classification: soil taxonomy, used by soil scientists, and the engineering classification, which groups soils by material types and engineering properties.

Soil Taxonomy

Soil scientists have developed a comprehensive and systematic classification of soils known as *soil taxonomy*, which emphasizes the physical and chemical properties of the soil profile. Soil taxonomy is useful for agricultural and related land-use purposes.

Engineering Classification of Soils

The *unified soil classification system*, widely used in engineering practice, is shown in Table 16.1. Because all natural soils are mixtures of coarse particles, including gravel and sand, fine particles, including silt and clay, and organic material, the major divisions of this system are coarse-grained soils, fine-grained soils, and organic soils. Each group is based on the predominant particle size or the abundance of organic material in the soil. Organic soils have a high organic content and are identified by their black or gray color and sometimes by an odor of hydrogen sulfide, which smells like rotten eggs.

16.7 Engineering Properties of Soils

The water table acts as a transition zone within Earth. Pores in rocks below the water table are saturated; those above are not. Soil above the water table has three distinct parts, or phases: solid material, liquid, and gas, such as air or carbon dioxide. A soil's usefulness is greatly affected by the variations in the proportions and structure of the three phases. The types of solid materials, the particle size, and the water content are probably the most significant variables that determine

TABLE 16.1 Unified Soil Classification System Used by Engineers

		Major Division		Group Symbol	Soil Group Name
COARSE-GRAINED SOILS (More than half of material larger than 0.074 mm)	GRAVELS	Clean gravels	Less than 5% fines	GW	Well-graded gravel
				GP	Poorly graded gravel
		Dirty gravels	More than 12% fines	GM	Silty gravel
				GC	Clayey gravel
	SANDS	Clean sands	Less than 5% fines	SW	Well-graded sand
				SP	Poorly graded sand
		Dirty sands	More than 12% fines	SM	Silty sand
				SC	Clayey sand
FINE-GRAINED SOILS (More than half of material smaller than 0.074 mm)	SILTS, NONPLASTIC			ML	Silt
				MH	Micaceous silt
				OL	Organic silt
	CLAYS, PLASTIC			CL	Silty clay
				CH	High plastic clay
				OH	Organic clay
Predominantly organics				PT	Peat and muck

Note: The value of 0.074 mm is the boundary between sand and silt that engineers use. Geologists use 0.063 mm for the same boundary.

engineering properties of soils. Important engineering properties are strength, sensitivity, compressibility, erodibility, hydraulic conductivity, corrosion potential, ease of excavation, and shrink-swell potential.

Soil Strength

Soil *strength* is the ability of a soil to resist deformation. It is difficult to generalize about the strength of soils. Numerical averages of the strength of a soil can be misleading, because soils are often composed of mixtures, zones, or layers of materials with different physical and chemical properties.

The strength of a particular soil type is a function of cohesive and frictional forces. *Cohesion* is a measure of the ability of very small silt and clay soil particles to stick together. The cohesion of particles in fine-grained soils is primarily the result of electrostatic forces between particles and is a significant factor in determining the strength of a soil. In partially saturated coarse-grained, sandy soils, moisture films between the grains may cause an apparent cohesion due to surface tension caused by the attraction of water molecules to each other at the surface or between soil grains (Figure 16.5). The principle of cohesion explains the ability of damp sand, which is cohesionless when dry, to stand in vertical walls in children's

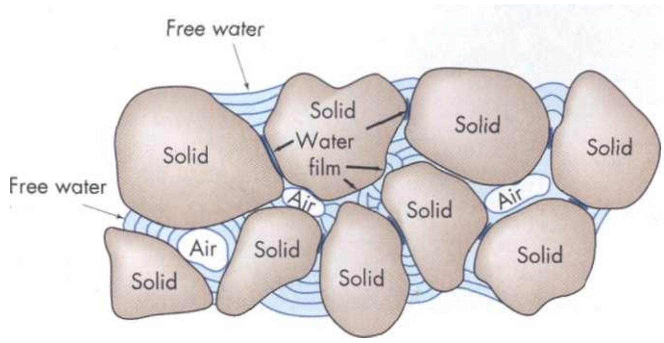


Figure 16.5 Water in soils
Partly saturated soil, showing particle-water-air relationships. Particle size is greatly magnified. The attraction between the water and the soil particles, or the surface tension, develops a stress that holds the grains together. This apparent cohesion is destroyed if the soil dries out or becomes completely saturated. *(After Pestrong, R. 1974. Slope stability. New York: American Geological Institute and McGraw-Hill)*

Figure 16.6 Apparent cohesion Children's sand castle. The surface tension of water molecules in the damp sand enables the walls of the castle to stand. *(John Lei/Stock Boston)*

sand castles on the beach (Figure 16.6).[10] Friction between grains also contributes to the strength of a soil. The total frictional force is a function of the density, size, and shape of the soil particles and of the weight of overlying particles that force the grains together. Frictional forces are most significant in coarse-grained soils rich in sand and gravel. Frictional forces are the reason why you do not sink far into the sand when walking on dry sand on beaches. Most soils are a mixture of coarse and fine particles, so the strength is usually the result of both cohesion and internal friction. Although it is difficult to generalize, clay-rich soils with weak clay minerals and organic-rich soils, such as peaty soils, tend to have lower strengths than coarser soils.

Vegetation may play an important role in soil strength. For example, tree roots may provide considerable cohesion through the binding characteristics of a continuous root mat or by anchoring individual roots to bedrock beneath thin soils on steep slopes (Figure 16.7).

Figure 16.7 Root strength Tree roots are helping to bind the particles of this riverbank soil together. *(Edward A. Keller)*

Soil Sensitivity

Soil sensitivity measures changes in soil strength resulting from disturbances such as vibrations or excavations. Sand and gravel soils with no clay are the least sensitive. As fine material becomes abundant, soils become more and more sensitive. Some clay soils may lose 75 percent or more of their strength after a disturbance.[11]

Figure 16.8 Leaning Tower of Pisa, Italy The lean is a result of differential settling of the soil. If correction measures had not been taken to strengthen the tower, it would have fallen over. *(D. & J. Heaton/Stock Boston)*

Soil Compressibility

Soil *compressibility* is a measure of a soil's tendency to consolidate, or decrease in volume. Compressibility is partially a function of the elastic nature of the soil particles and is directly related to the settling of structures such as the world-famous Leaning Tower of Pisa in Italy (Figure 16.8). Excessive settling will crack foundations and walls. Coarse materials such as gravels and sands have a low compressibility, and settling will be considerably less in these materials than in highly compressible fine-grained or organic soils.

Erodibility

Soil ***erodibility*** refers to the ease with which soil materials can be removed by wind or water. Soils with a high erosion factor include unprotected silts and sands. Cohesive soils, which are more than 20 percent clay, naturally cemented soils, or coarse gravel-rich soils are not as easily eroded by wind or water and therefore have a low erosion factor.

Hydraulic Conductivity

Hydraulic conductivity (K) is a measure of the ease with which water moves through a material. Hydraulic conductivity is measured in units of velocity, centimeters per second or centimeters per hour (see the discussion of groundwater in Chapter 12). Saturated clean gravels or sands have the highest K values (from 5 to greater than 50 cm per hour, or 2 to greater than 20 in. per hour). As fine particles in a saturated mixture of clean gravel and sand increase, K decreases. Saturated clays generally have a very low K, less than 0.025 cm (0.01 in.) per hour.[6] Hydraulic conductivity in unsaturated soils is complex; fine-grained, unsaturated soils actually pull or suck water and hold it tightly. Hydraulic conductivity is very important in many soil environmental problems related to soil drainage, the movement of liquid pollutants in soils, and land-use potential for agriculture, waste disposal, and construction.

Corrosion Potential

Corrosion is a slow weathering or chemical decomposition that proceeds from the surface into the ground. All objects buried in the ground—pipes, cables, anchors, fence posts—are subject to corrosion. The corrosiveness of a particular soil depends on the chemistry of the soil, the buried material, and the amount of water available.[12]

Ease of Excavation

Ease of excavation pertains to the procedures, and hence the equipment, required to remove soils during construction. There are three general categories of excavation techniques. *Common excavation* is accomplished with an earth mover, backhoe, or bulldozer. This equipment essentially removes the soil without having to scrape it first; most soils can be removed by this process. *Rippable excavation* requires breaking up the soil with special ripping teeth before it can be removed. For example, a tightly compacted or cemented soil would require rippable excavation. *Blasting* or *rock cutting* is the third, and often the most expensive, category; a hard silica cemented soil might need to be cut with a jackhammer before being removed.

Shrink-Swell Potential

Shrink-swell potential refers to the tendency of a soil to gain or lose water. Soils that tend to increase the submicroscopic flat particles, or plates, of certain clay minerals. The plates are composed primarily of silica, aluminum, and oxygen atoms, and layers of water are added between the plates as the clay expands or swells (Figure 16.9a).[13] Expansive soils tend to absorb large quantities of water and expand. Cracks in the ground form when the soil dries out and contracts (Figure 16.9c). *Montmorillonite* is the I common clay mineral associated with most expansive soils. With sufficient water, pure montmorillonite may expand up to 15 times its original volume; fortunately, most soils contain limited amounts of this clay mineral, so it is unusual for an expansive soil to swell beyond 25 percent to 50 percent. However, an increase in volume of more than 3 percent is considered potentially hazardous.[13]

Expansive soils in the United States cause significant environmental problems. As one of our most costly natural hazards, expansive soils are responsible for several billions of dollars in damages annually to highways, buildings, and other structures. Every year more than 250,000 new houses are constructed on expansive soils. Of these, about 60 percent will experience some minor damage, such as

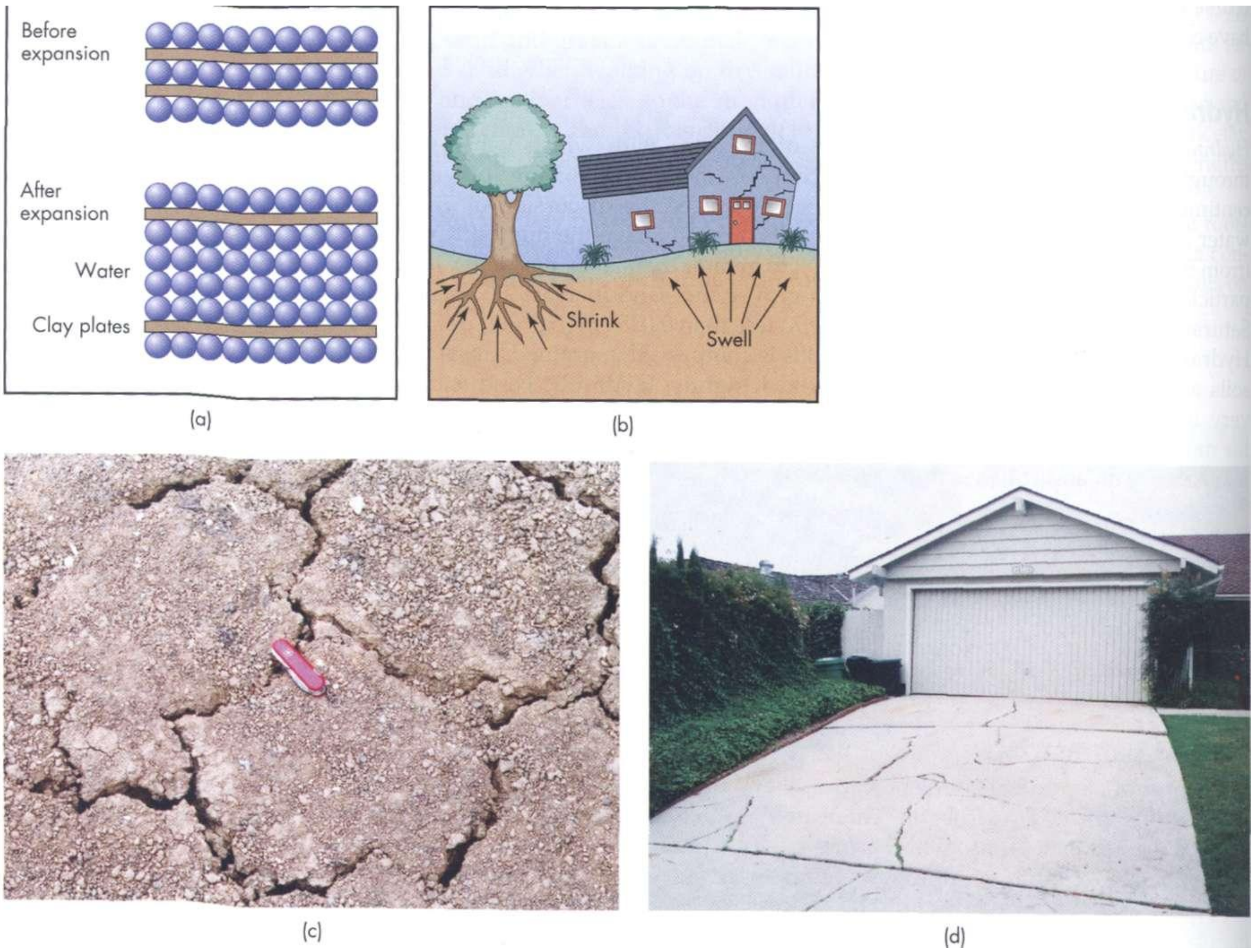


Figure 16.9 Expansive soils (a) Expansion of a clay (montmorillonite) as layers of water molecules are incorporated between clay plates, (b) Effects of soil's shrinking and swelling at a home site. *(After Mathewson, C. C, and Castleberry IP., II. Exp.......|s: Their engineering geology. Texas A&M University)* (c) Cracks from a soil that has contracted, (d) Driveway cracked by expansion of clay soil under the foundation. *(Edward A. Keller)*

cracks in the foundation, walls, driveway, or walkway (Figure 16.9b, d); 10 percent will be seriously damaged, some beyond repair.[14,15]

Structural damage on expansive soils is caused by volume changes in the soil in response to changes in moisture content. Factors that affect the moisture content of an expansive soil include climate, vegetation, topography, drainage, and quality of construction.[14] Builders in regions that have a pronounced wet season followed by a dry season allow for a regular shrink-swell sequence. These regions, such as the southwestern United States, are more likely to experience an expansive soil problem than are regions where precipitation is more evenly distributed throughout the year. Vegetation can cause changes in the moisture content of soils. Because large trees draw and use a lot of local soil moisture, especially during a dry season, they facilitate soil shrinkage. Therefore, in areas with expansive soil, trees should not be planted close to the foundations of light structures, such as homes (Figure 16.9b).

Topography and drainage are also significant factors for evaluating expansive soils. Adverse topographic and drainage conditions cause water to form ponds around or near structures, increasing the swelling of expansive clays. However, homeowners and contractors can do a great deal to avoid this problem. Proper design of subsurface drains and rain gutters can minimize expansive soil damages by improving drainage, as may designing and constructing foundations to accommodate some shrinking and swelling of the soil.[14]

Clearly, some soils are more desirable than others for specific uses. Although planners concerned with land use will not conduct soil tests to evaluate the engineering properties of soils, they will be better prepared to design with nature and take advantage of geologic conditions if they understand the basic terminology and principles of Earth materials. Our discussion of engineering properties established two general principles. First, because of their low strength, high sensitivity, high compressibility, low permeability, and variable shrink-swell potential, clay soils should be avoided in projects involving heavy structures, structures with minimal allowable settling, or projects needing well-drained soils. Second, soils that have a high corrosive potential or that require other than common excavation should be avoided if possible. If such soils cannot be avoided, extra care, special materials and techniques, and higher-than-average initial costs—including planning, design, and construction—must be expected. The secondary costs—that is, the operation and maintenance costs of these projects—may also be greater.

16.8 Rates of Soil Erosion

Rates of soil erosion are measured as a volume, mass, or weight of soil that is removed from a location within a specified time and area, for example, kilograms per year per hectare. Soil erosion rates vary with the engineering properties of the soil, land use, topography, and climate.

There are several approaches to measuring rates of soil erosion. The most direct method is to make actual measurements on slopes over a period of at least several years and use these values as representative of what is happening over a wider area and longer time span. This approach is rarely used, however, because data from individual slopes and drainage basins are very difficult to obtain. A second approach is to use data obtained from resurveying reservoirs to calculate the change in the reservoirs' storage capacity of water; the depletion of storage capacity is equivalent to the volume of sediment eroded from upstream soils. A third approach is to use an equation to calculate rates of sediment eroded from a particular site. One of the most commonly used equations is the Universal Soil Loss Equation.[16] This equation uses data on rainfall, runoff, the size and shape of the slope, the soil cover, and erosion-control practices to predict the amount of soil moved from its original position[17] (see A Closer Look: Universal Soil Loss Equation).

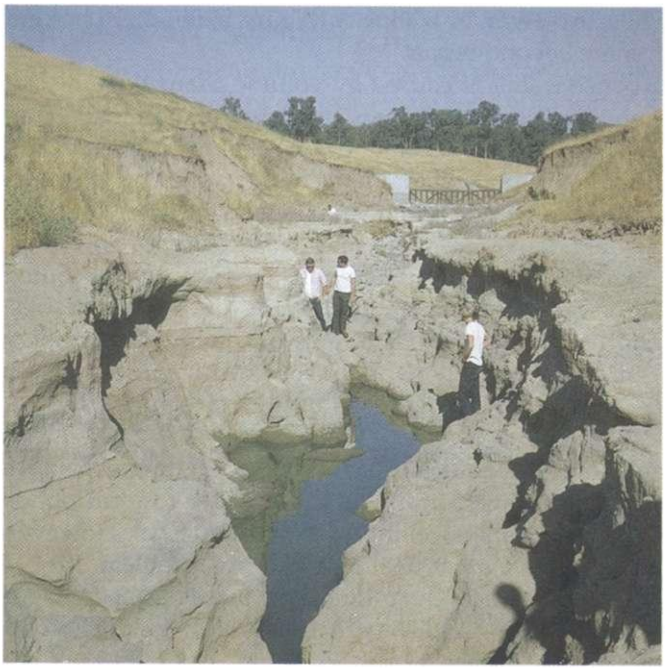


Figure 16.10 Serious soil erosion and gully formation in central California related to diversion of runoff water. The surface was essentially ungullied several months before the photograph was taken. *(Edward A. Keller)*

16.9 Sediment Pollution

Sediment is one of our greatest pollutants. In many areas, it chokes streams; fills in lakes, reservoirs, ponds, canals, drainage ditches, and harbors; buries vegetation; and generally creates a nuisance that is difficult to remove. Natural pollutional sediment—eroded soil—is truly a resource out of place. It depletes soil at its site of origin (Figure 16.10), reduces the quality of the water it enters, and may deposit unwanted sediment on productive croplands or other useful land (Figure 16.11).[18]

Sources of the sediment include land disturbed for agriculture, land overgrazed by animals such as sheep or cattle, urban construction sites, land recently logged or burned, and land disrupted by mining. Sediment pollution affects rivers, streams, lakes, and even the ocean. Unfortunately, the problem promises to be with us indefinitely. One solution to sediment pollution is to implement sound conservation practices, particularly in urbanizing areas, where tremendous quantities of sediment are produced during construction (see Case History: Reduction

Figure 16.11 Soil erosion has resulted in unwanted red sediment at this site in Charlotte, North Carolina. *(Edward A. Keller)*

[\ CLOSER LOOK Universal Soil Loss Equation

The Universal Soil Loss Equation is

$$A = RKLSCP$$

where

A = the long-term *average* annual soil loss for the site being considered
R = the long-term rainfall *runoff* erosion factor
K = the soil erodibility index
L = the hillslope/Iengf/z factor
S = the hillslope/gradient, or *slope* factor
C = the soil *cover* factor
P = the erosion-control *practice* factor

The advantage of using this equation is that once the various factors have been determined and multiplied together to produce predicted soil loss, conservation practices may be applied through factors C and P to reduce the soil loss to the desired level. For slopes that are amenable to shaping, factors K, L, and S may also be manipulated to achieve desired sediment loss results. This equation is particularly valuable for evaluating construction sites and areas along corridors such as pipelines and highways. When planning construction sites, planners can use the Universal Soil Loss Equation to predict the impact of sediment loss on local streams and other resources and to develop management strategies for minimizing this impact.[16,17]

of Sediment Pollution, Maryland). Another solution is to use sediment control basins, which are designed to trap and control sediment; they must be periodically cleared out to operate effectively. A generalized cross section of a sediment control basin is shown in Figure 16.12.

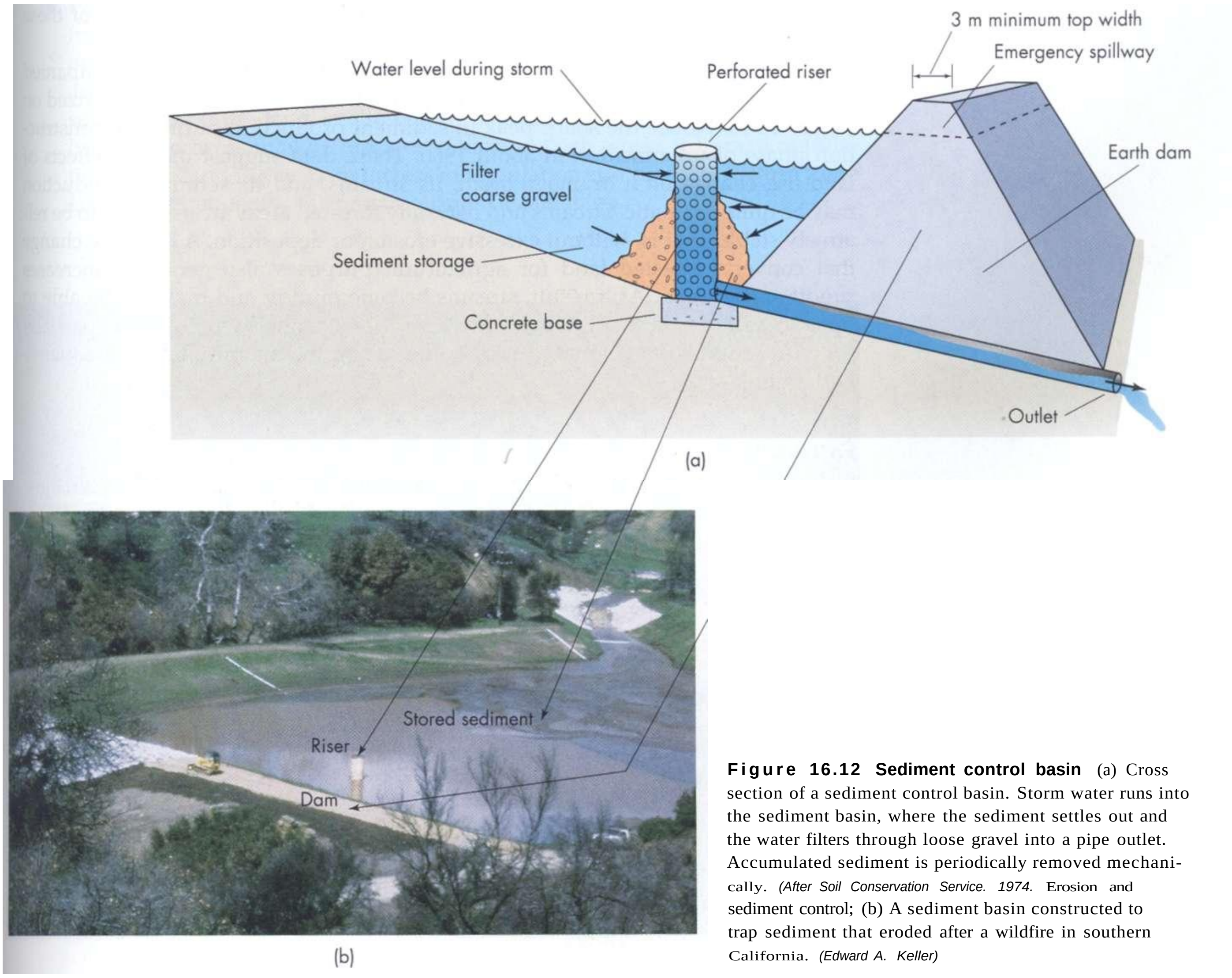


Figure 16.12 Sediment control basin (a) Cross section of a sediment control basin. Storm water runs into the sediment basin, where the sediment settles out and the water filters through loose gravel into a pipe outlet. Accumulated sediment is periodically removed mechanically. *(After Soil Conservation Service. 1974.* Erosion and sediment control; (b) A sediment basin constructed to trap sediment that eroded after a wildfire in southern California. *(Edward A. Keller)*

CASE HISTORY Reduction of Sediment Pollution, Maryland

A study in Maryland demonstrated that sediment control measures can reduce sediment pollution in an urbanizing area.[19] The suspended sediment transported by the northwest branch of the Anacostia River near Colesville, Maryland, with a drainage area of 55 km^2 (21 mi^2), was measured over a 10-year period. During that time, construction within the basin involved about 3 percent of the area each year. The total urban land area in the basin was about 20 percent at the end of the 10-year study.

Sediment pollution was a problem in the area because the soils are highly susceptible to erosion; moreover, there is sufficient precipitation to ensure their erosion when construction has removed the vegetative cover. Most of the sediment is transported during spring and summer rainstorms.[19] A sediment-control program was initiated, and the sediment yield was reduced by about 35 percent. The program utilized basic sediment-control principles such as tailoring development to the natural topography, exposing a minimal amount of land, providing protection for exposed soil, minimizing surface runoff from critical areas, and trapping eroded sediment on construction sites. Specific measures included scheduled grading to minimize the time of soil exposure, mulch application and temporary vegetation to protect exposed soils, sediment diversion berms, stabilized channels, and sediment basins. The Maryland study concluded that even further sediment control can be achieved by both scheduling major grading during periods of low erosion potential and designing improved sediment traps to control runoff during storms.[19]

16.10 Land Use and Environmental Problems of Soils

Human activities affect soils by influencing the pattern, amount, and intensity of surface-water runoff, erosion, and sedimentation. The most important of these human influences is the conversion of natural areas to various land uses.

The estimated and observed variation in sediment yield that accompanied changes in land use in the Piedmont region from 1800 to 2000 are summarized on Figure 16.13. Notice the sharp peak in sediment production during the construction phase of urbanization in about 1960. These data suggest that the effects of land-use change on a drainage basin, its streams, and its sediment production may be quite dramatic. Streams and naturally forested areas are assumed to be relatively stable, that is, without excessive erosion or deposition. A land-use change that converts forested land for agricultural purposes also generally increases runoff and erosion. As a result, streams become muddy and may not be able to transport all the sediment delivered to them. The channels will therefore partially fill with sediment, or *aggrade*, possibly increasing the magnitude and frequency of flooding.

Agriculture

In the past 50 years, soil erosion and overuse of soils caused by intensive agriculture have damaged about 10 percent of the world's best agricultural land. It is

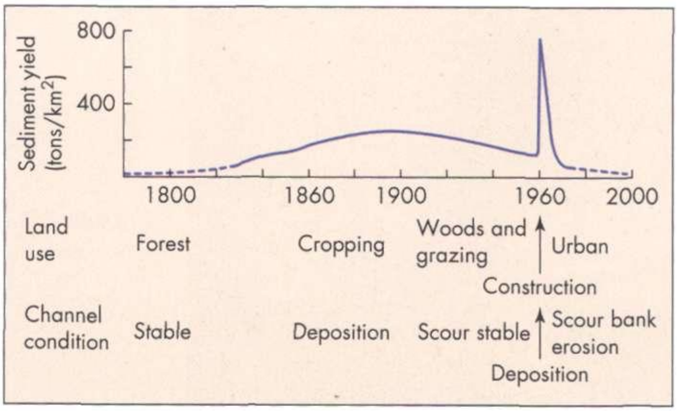


Figure 16.13 Land use and sediment yield Effect of land use on sediment yield and channel condition. The graph shows observed and estimated changes in the Piedmont region of the eastern United States, from before the beginning of extensive farming through a period of construction and urbanization (200 tons per square kilometer = 500 tons per square mile). *(After Wolman, M. 1966. Geografiska Annaler 49A)*

estimated that in the United States approximately one-third of the *topsoil,* the most fertile soil near the surface that supports vegetation, has been lost to erosion.[20]

Traditional agriculture, which involves plowing the soil in straight lines, or furrows, is particularly damaging. Removal of vegetation exposes the soil to erosion by wind and water. Even on gentle slopes, furrows may channel the water downslope, increasing the erosion potential. Although new soil is constantly forming, soils form very slowly, from a rate of about 1 mm (0.04 in.) in several decades to as much as 1 mm (0.04 in.) per year. The key to sustaining soil resources is to reduce erosion to a rate less than the rate that soils naturally form. Some practices to sustain soils are[20]

- **our plowing.** This involves plowing with the natural topography of the land. Furrows are plowed perpendicular to the slope of the land rather than in the downslope direction. This is one of the most effective ways to reduce erosion by running water and is widely used (Figure 16.14).
- **No-till agriculture.** This eliminates plowing altogether, greatly reducing sion. No-till agriculture is an integrated plan to plant and harvest crops without plowing while suppressing weeds and other pests.
- **racing slopes.** Soil erosion on steep slopes can be managed and minimized by terracing slopes to produce flat areas for farming. Retaining walls of stone or other materials are used to form terraces and stabilize the slope. Terracing is widely used on farms around the world (Figure 16.15).
- ***Planting more than one crop.*** This is most effective on small farms in the tropical rain forest and other areas. The forest trees are cut in small patches of land, and some smaller trees and plants are left in place. Several crops are planted among the remaining natural vegetation (Figure 16.16). After several years, the land is allowed to recover. When the forest has grown back, the process may be repeated. This approach works if human population on the land is low. With increased population and pressure to farm more land more frequently, the practice is not sustainable.

Figure 16.14 Contour plowing can significantly reduce soil erosion. This scene is near McGregor, Iowa. *(Alex S. MacLean/Peter Arnold, Inc.)*

Figure 16.15 Terraced slopes reduce soil erosion and produce flat land for farming. These rice paddies on terraces are in Bali, Indonesia. *(Fred Bruemmer/Peter Arnold, Inc.)*

Urbanization

The conversion of agricultural, forested, or rural land to highly urbanized land causes dramatic changes. During the construction phase of a conversion there is a tremendous increase in sediment production, which may be accompanied by a increase in runoff (Figures 16.13 and 16.17). The response of streas in the area is complex and may include both channel erosion and deposition, resulting in wide, shallow channels. The combination of increased runoff and shallow channels increases the flood hazard. After the construction phase, the land is mostly covered with buildings, parking lots, and streets, so the sediment yield drops to a low level. Streams respond to the lower sediment yield and higher runoff by eroding their channels, which become deeper. However, because of the large impervious areas and the use of storm sewers, runoff increases, again increasing the risk of flooding.

The process of urbanization directly affects soils in several ways:

- Soil may be scraped off and lost. Once sensitive soils are disturbed, they may have lower strengths when they are remolded.
- Materials may be brought in from outside areas to fill a depression before construction, resulting in a much different soil than was previously there.
- Draining soils to remove water may cause *desiccation*, or drying out, and other changes in soil properties.
- Soils in urban areas are susceptible to soil pollution resulting from deliberate or inadvertent addition of chemicals to soils. This problem is particularly serious if hazardous chemicals have been applied.

Figure 16.16 Multiple crops Farming a small plot of land in the rain forest of Nigeria, producing several crops. *(Still Pictures/Peter Arnold, inc.)*

Off-Road Vehicles

Urbanization is not the only land use that causes increased soil erosion and hydrologic changes. In recent years, the popularity of off-road vehicles (ORVs) has

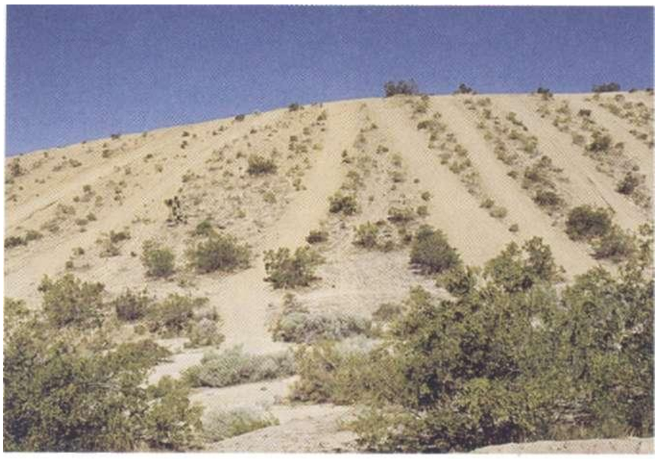
(a)

(b)

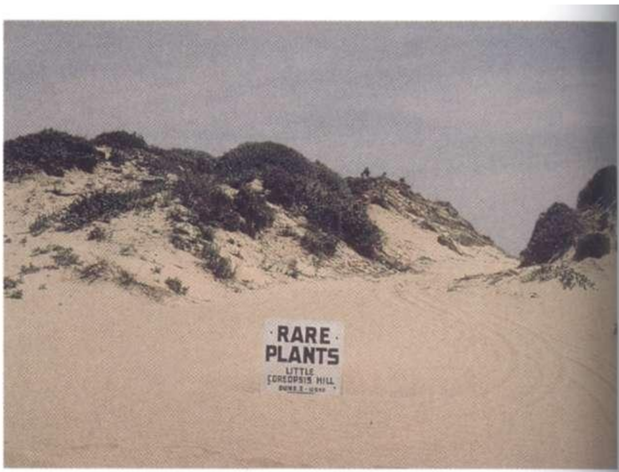
Figure 16.17 Soil erosion in the urban environment (a) Urbanization and the construction of freeway on-ramps can contribute to soil erosion and increased sediment production. This eroding embankment is near the University of California, Santa Barbara, and the community of Isla Vista, (b) A few years after erosion control measures were taken by planting vegetation. *(Edward A. Keller)*

increased enormously; demand for recreational areas to pursue this interest has led to serious environmental problems as well as conflicts between users of public lands.

There are now millions of ORVs, many of which are invading the deserts, coastal dunes, and forested mountains of the United States. Problems associated with



(a)



(b)

(c)

Figure 16.18 Off-road vehicles Serious erosion problems caused by off-road vehicle use (a) in mountains and (b) on coastal dunes. *(Edward A. Keller)* (c) An ORV churning up sand on a coastal dune. *(Los Angeles Times Photo by Steve Osman)*

ORVs are common, from the shores of North Carolina and New York to sand dunes in Michigan and Indiana to deserts and beaches in the western United States. A single motorcycle need travel only 8 km (5 mi) to have an impact on an area measuring 1,000 m^2 (10,765 ft^2), and a four-wheel-drive vehicle has an impact over the same area by traveling only 2.4 km (1.5 mi). In some desert areas, the tracks produce scars that may remain part of the landscape for hundreds of years.[21,22]

The major areas of environmental problems caused by ORVs are soil erosion, changes in hydrology, and damage to plants and animals. Off-road vehicles cause direct mechanical erosion and facilitate wind and water erosion of materials loosened by their passing (Figure 16.18). Runoff from ORV sites is as much as eight times greater than for adjacent unused areas, and sediment yields are comparable to those found on construction sites in urbanizing areas.[2] Hydrologic changes from ORV activity result primarily from near-surface soil compaction that reduces the ability of the soil to absorb water. Furthermore, water already in the soil becomes more tightly held and thus less available to plants and animals. In the Mojave Desert, tank tracks produced 50 years ago are still visible, and the compacted soils have not recovered.[22] Compaction also changes the variability of soil temperature. This effect is especially apparent near the surface, where the soil becomes hotter during the day and colder at night. Animals are killed or displaced and vegetation is damaged or destroyed by intensive ORV activity. The damage results from a combination of soil erosion, compaction, temperature change, and moisture content change.[22] "

Figure 16.19 Soil erosion by biking and walking Deep ruts have been excavated by bicyles and walking in a sandy soil at this California site. *(Edward A. Keller)*

There is little doubt that as a management strategy some land must be set aside for ORV use. However, how much land should be involved, and how can environmental damage be minimized? Sites should be chosen in closed basins with minimal soil and vegetation variation. The possible effects of erosion by wind, must be evaluated carefully, as must the sacrifice of nonrenewable cultural, biological, and geologic resources.[21] A major problem remains: Intensive ORV use is incompatible with nearly all other land use, and it is very difficult to restrict damages to a specific site. Material removed by mechanical, water, and wind erosion will always have an impact on other areas and activities.[21,22]

In recent years the demand for self-propelled vehicles has been increasing. Use of off-road mountain bikes has grown dramatically and is having an impact on the environment. Bicycles have damaged mountain meadows, and their intensive use contributes to trail erosion (Figure 16.19). Mountain bike users are lobbying to gain entry into even more locations in the national forests, parks, and wilderness areas. Their position states that one bicycle causes less erosion than one horse. Although this is generally true, mountain bikes are cheaper and easier to maintain than horses; therefore, there are many more people riding mountain bikes than there are riding horses. Thus, the cumulative effect of bicycles on trails may be greater than that of horses. Also, hikers and other visitors may not mind seeing animals such as horses in wilderness areas but may be less receptive to bicycles, which are fast and almost silent (you can't hear them coming). Wilderness management plans will have to be developed to ensure that overenthusiastic people do not damage sensitive environments.

16.11 Soil Pollution

Soil pollution occurs when materials detrimental to people and other living things are inadvertently or deliberately applied to soils (see Case History: Times Beach, Missouri, at the beginning of this chapter). Many types of materials, including organic chemicals such as hydrocarbons or pesticides, or heavy metals such; selenium, cadmium, nickel, or lead, may act as soil contaminants. Soils, partici larly those with clay particles, can also act to selectively attract, absorb, or bind toxins and other materials that otherwise would contaminate the environment. Soils may also contain organisms that break down certain contaminants into less harmful materials. As a result, soils offer opportunities to reduce environmental | pollution. However, contaminants in soils and the products of their breakdown by soil and biochemical processes may be toxic to ecosystems and humans if they become concentrated in plants or are transported into the atmosphere or water.[5]

Problems arise when soils intended for uses other than waste disposal are contaminated, or when people discover that soils have been contaminated by previous uses. Houses and other structures, such as schools, have been built over sites where soils have been contaminated. At many sites, contamination from old waste-disposal facilities or from dumping of chemicals is now being discovered; some of these sites are being treated. However, treatment of soils to remove contaminants can be a very costly endeavor. Treatments vary from excavation and disposal to incineration or bioremediation. Often, bioremediation is done on the pollution site and does not require excavating and moving large quantities of contaminated soil (Figure 16.20).[5]' In recent years, soil and water contaminated by leaking underground tanks have become a significant environmental concern. Businesses are now adding systems to monitor storage tanks so that leaks can be detected before significant environmental damage occurs.

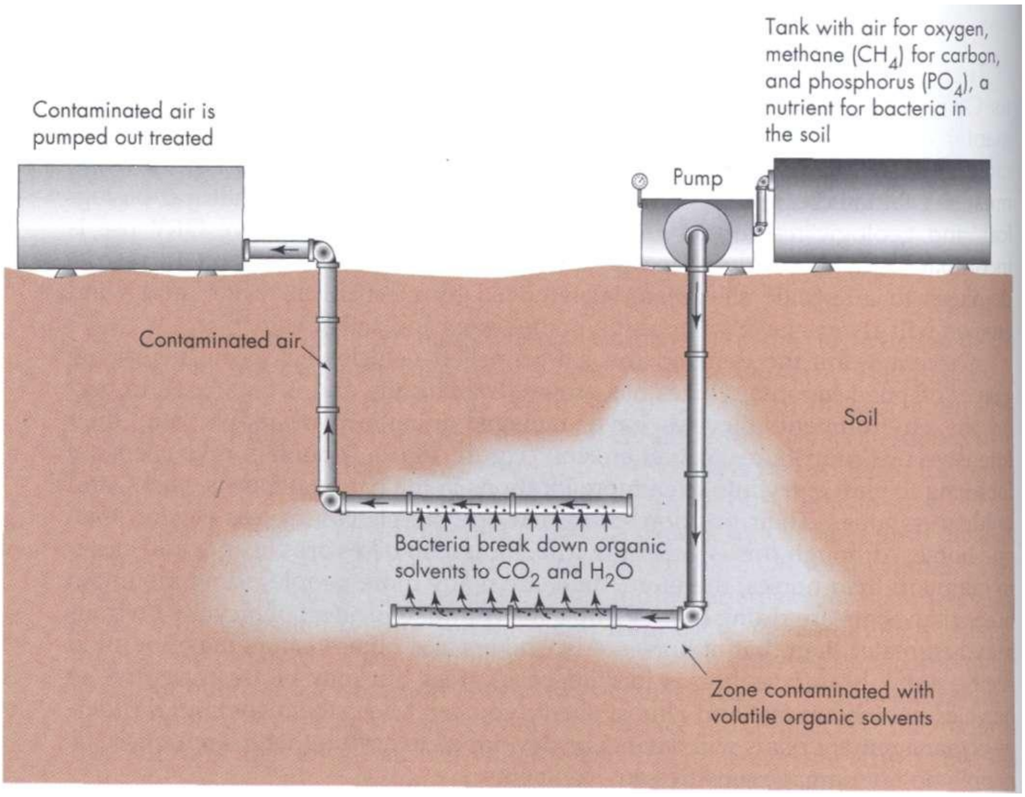


Figure 16.20 Bioremediation Idealized diagram illustrating the process of enhanced bioremediation of soil contaminated by an organic solvent. Methane (CH_4), phosphorus (PO4), and air (with O_2) are nutrients pumped intermittently into the contaminated area and released from the lower slotted pipe. The upper pipe (also slotted) sucks contaminated air from the soil. The nutrients stimulate the growth of bacteria. The supply of methane, a carbon source, is then stopped and the carbon-hungry bacteria go after the inorganic solvents, degrading them to carbon dioxide and water as part of their life cycle. This type of process can significantly reduce the contaminated soil's treatment time and cost. *(Modified after Hazen, T. C. 1995. Savanna River site—A test bed for cleanup technologies.* Environmental Protection, *April: 10-16)*

16.12 Soil Surveys and Land-Use Planning

The best use of land is greatly determined by its soils; therefore, a report called a soil survey is an important part of planning for nearly all engineering projects. A soil *survey* should include soil descriptions; soil maps showing the horizontal and vertical extent of soils; and results of tests to determine grain size, moisture content, and strength. The purpose of the survey is to provide necessary information for identifying potential problem areas before construction.[6]

The information from detailed soil maps can be extremely helpful in land-use planning if it is used in combination with guidelines for the proper use of soils. Soils can be rated according to their limitations for a specific land use, such as housing, light industry, septic-tank systems, roads, recreation, agriculture, and forestry.

SUMMARY

Engineers define soil as Earth material that may be removed without blasting, whereas to a soil scientist, a soil is solid Earth material that can support rooted plant life. A basic understanding of soils and their properties is becoming crucial in several areas of environmental geology, including land-use planning, waste disposal, and evaluation of natural hazards such as flooding, landslides, and earthquakes.

Soils result from interactions of the rock and hydrologic cycles with biogeochemical processes. As open systems, they are affected by variables such as climate, topography, parent material, time, and biological activity. Soil-forming processes tend to produce distinctive soil layers, or horizons, defined by the processes that formed them and the type of materials present. The processes of leaching, oxidation, and accumulation of materials in various soil horizons are particularly important. Development of the argillic B horizon, for example, depends on the translocation of clay minerals from upper to lower horizons. Three important properties of soils are color, texture or particle size, and structure (the aggregation of particles).

A soil may be considered a complex ecosystem in which many types of living things convert soil nutrients into forms that plants can use. Soil fertility is the capacity of the soil to supply nutrients needed for plant growth. Soils may go through natural stages of building, sustaining, and degrading. Each stage has important implications for ecosystems.

Soil has a solid phase consisting of mineral and organic matter; a gas phase, including mostly air; and a liquid phase, which consists mostly of water. Water may flow vertically or laterally through the pores of a soil. The flow is either saturated, in which all pore space is filled with water, or, more commonly, unsaturated, in which pore spaces are partially filled with water. Soil moisture and how water moves through soils are becoming important topics in environmental geology.

Several types of soil classification exist, but none of them integrates both engineering properties and soil processes. Environmental geologists must be aware of both the soil-science classification, or soil taxonomy, and the engineering classification, known as the unified soil classification system.

A basic understanding of the engineering properties of soils is crucial in many environmental problems. These properties include soil strength, sensitivity, compressibility, erodibility, hydraulic conductivity, corrosion potential, ease of excavation, and shrink-swell potential. Shrink-swell potential is particularly important because expansive soils in the United States cause significant environmental problems and constitute one of our most costly natural hazards.

Rates of soil erosion can be determined by direct observation of soil loss from slopes, by measurement of accumulated sediment in reservoirs, or by calculation using an equation. A common method is to apply the Universal Soil Loss Equation, which uses variables that affect erosion to predict the amount of soil that will be moved from its original position. These variables can often be manipulated as part of a management strategy to minimize erosion and sediment pollution from a particular site. Sediment, both natural and human-made, may be one of our greatest pollutants. It reduces water quality and chokes streams, lakes, reservoirs, and harbors. With good conservation practice, sediment pollution can be much reduced.

Sustaining soils requires that rates of soil erosion be less than rates of soil formation. Land use and surface-water manipulation affect the pattern, amount, and intensity of surface-water runoff, soil erosion, and sediment pollution. In agricultural areas, soil erosion may be minimized most effectively by contour plowing, no-till agriculture, terracing slopes, and planting more than one crop.

Urbanization often involves loss of soil, change of soil properties, accelerated soil erosion during construction, and pollution of soils. Use of motorized and nonmotorized off-road vehicles causes soil erosion, changes in hydrology, and damage to plants and animals.

Soil pollution occurs when hazardous materials are inadvertently or deliberately added to soils. Pollution limits the usefulness of soils or even renders them hazardous to life. Processes in soils may also be useful in reducing or eliminating contaminants from soil. The deliberate use of soil processes to eliminate contamination is known as bioremediation.

Soil surveys are extremely useful in land-use planning. Soils can be rated according to their limitations for various land uses. This information can be combined with a detailed soils map to produce a simplified map that shows a soil's limitations for a specific use.

Unit 5 - Geological resources and environmental geochemistry

Some people say: "If it isn't grown, it has to be mined". We depend on metal mining for many of the material goods that make our lives pleasant and convenient, but we get much more from the earth than metals, such things as petroleum resources and the related chemicals, industrial minerals, and the most precious of all commodities – clean water.

Resources from the Earth

5.1 Metals and mining

Mining has always been a major part of Canada's economy. Canada has some of the largest metalliferous provinces and mineral deposits, and for the past 150 years Canada has been one of the most important suppliers of metals to the world. In order to understand the environmental impact of the exploitation of metal deposits it is necessary to understand both what makes a mineral deposit, and the geological nature of some of the important deposit types.

Metals and mining

Background levels and metal enrichment

A metal deposit is a body of rock in which one or more metals has been enriched to the point of being economically viable for recovery. Some geological background levels for important metals are shown in Table 5.1, along with the typical grades necessary to make a viable deposit, and the corresponding concentration factors.

Metal	Typical background level*	Typical economic grade*	Concentration factor
Copper	40 ppm	10,000 ppm	250 times
Gold	0.003 ppm	6 ppm	2000 times
Lead	10 ppm	50,000 ppm	5000 times
Molybdenum	1 ppm	1000 ppm	1000 times
Nickel	25 ppm	20,000 ppm	800 times
Silver	0.1 ppm	1000 ppm	10,000 times
Uranium	2 ppm	10,000 ppm	5000 times
Zinc	50 ppm	50,000 ppm	1000 times

* Background levels vary widely depending on the rock type. Grades also vary widely depending on economic and political conditions. The values shown here are broad approximations.

Background levels and typical economic grades of some important metals

It is clear that some very significant concentration must take place to form a mineable deposit. This concentration may occur during the formation of the host rock - as is the case with some magmatic and volcanogenic deposits - but in most cases the concentration occurs after the rock is formed, through a number of different types of processes. Some of these are discussed below.

Metal concentration

The grade at which a mineral deposit will be economically viable depends on a wide range of factors, including the following, which are arranged in approximate order of importance:

Economic grade

- the current prices of the commodities being mined,
- the size and grade of the deposit,
- the depth of the deposit, the type of rocks in which it is found, and the shape and spatial continuity of the ore zone (i.e. what type of mining method can be used),
- the taxes, business climate and environmental laws of the jurisdiction in which the deposit is situated,
- the proximity to infrastructure, including transportation, energy, labour force, and water and other raw materials, and
- the metallurgical characteristics of the ore (i.e. how easy it is to extract the metal).

Economic viability

Many of these factors vary dramatically over time, and a metal deposit that is economically viable today may be uneconomic within a few years - and vice versa. Furthermore, the labour, mining and environmental regulations, the taxes and the infrastructure vary significantly from place to place, so a deposit which is not viable in a place like British Columbia[1], may be viable in another province, or in another country - like Peru or Indonesia.

Magmatic deposits

Magmatic deposits

A magmatic deposit is one in which the metal concentration takes place primarily during the formation and emplacement of the magma. Most of the nickel mined in the world comes from magmatic deposits such as those in Sudbury (Ontario), Thompson (Manitoba) and Voiseys Bay (Labrador). The magmas from which these deposits are formed are of mafic or ultra-mafic composition (they are derived from the mantle), and therefore they have relatively high nickel and copper contents to begin with (as much as 100 times that of normal rocks in the case of nickel). These elements are further concentrated within the magma as a result of addition of sulphur from partial melting of the surrounding rocks. The heavy nickel and copper sulphide minerals (pentlandite - $(Fe,Ni)_9S_8$ and chalcopyrite - $CuFeS_2$) are then concentrated further still by gravity segregation (i.e. settling towards the bottom of the magma chamber). Associated minerals include pyrite, pyrrhotite and sphalerite, and in some cases there are significant concentrations of platinum-bearing minerals.

Most of these types of deposits around the world are Precambrian in age - probably because the mantle was significantly hotter at that time and the necessary ultramafic magmas were more likely to exist close to the surface.

Volcanogenic massive sulphide deposits

Volcanogenic massive sulphide deposits

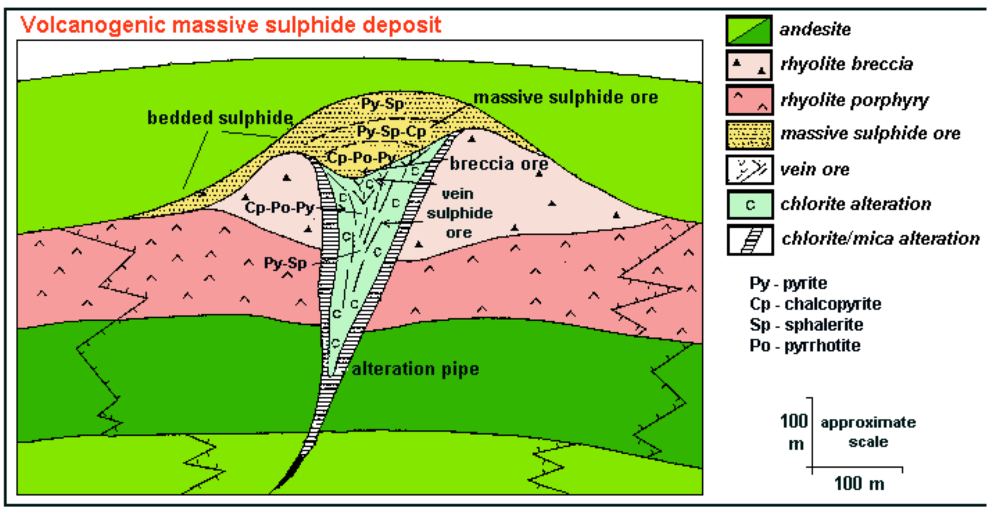
Much of the copper, zinc, lead, silver and gold mined in Canada comes from "massive sulphide" deposits associated with submarine volcanism (VMS deposits). Examples are the deposits at Kidd Creek, Ontario, at Flin Flon on the Manitoba-Saskatchewan border, and at Myra Falls (Buttle Lake) on Vancouver

[1] Compared to some places, including other provinces, British Columbia has fairly stringent environmental regulations, and both political and taxation environments which are not well-liked by the mining industry.

Island.

Black smokers

VMS deposits are derived from the solutions discharged at high-temperature (250 to 300° C) at ocean-floor vents, both in areas of subduction-zone volcanism and at spreading ridges (see figure below). The environment is similar to that associated with modern-day *black smokers*[2]. They are called massive-sulphide deposits because the sulphide minerals (including pyrite, sphalerite, chalcopyrite and galena) are present at very high concentrations (making up the majority of the rock in some cases). The metals and the sulphur are leached out of the sea-floor rocks by convecting groundwater driven by the volcanic heat. The volcanic material is extruded in the same area at the same general time as the accumulation of sulphides. A diagnostic feature of volcanogenic deposits formed in an island-arc setting is the presence of felsic volcanic rocks, including rhyolite. After their initial deposition at a vent area, the deposits of sulphide minerals and volcanic material are commonly transported down-slope by slumping. This can lead to banded textures.



Typical features of a volcanogenic massive sulphide deposit

Most such deposits in Canada are Precambrian in age, but some are younger (including Myra Falls which is in Devonian **Sicker Group** rocks - around 350 m.y.). Similar deposits in other parts of the world have a wide range of ages.

Sedimentary exhalative deposits

Sedimentary exhalative deposits

Sedimentary exhalative (sedex) deposits are important sources of lead, zinc and silver in Canada and elsewhere. Examples include the famous Sullivan Mine near to Kimberly, as well as numerous deposits in the Yukon and northern British Columbia.

[2] There is a lot of information on the net about black smokers. If you're interested, have a look at this site from the American Museum of Natural History: http://www.amnh.org/nationalcenter/expeditions/blacksmokers/black_smokers.html

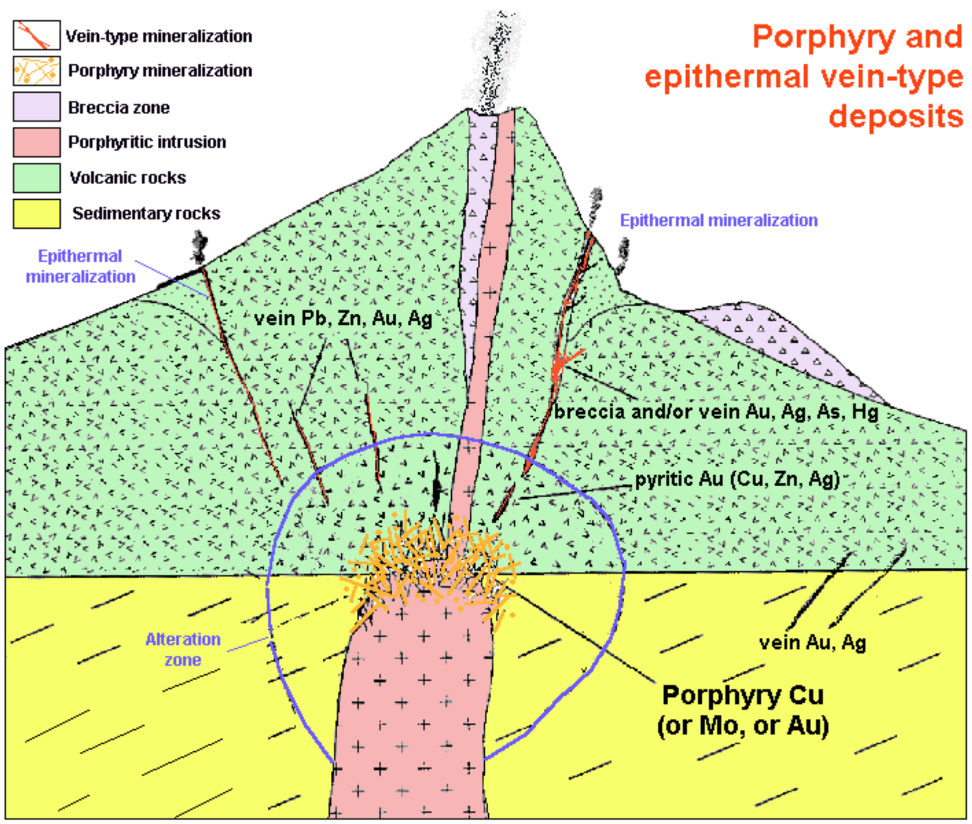
Sedex deposits have some similarities to VMS deposits, except that the host rocks are predominantly sedimentary as opposed to volcanic. They are also related to a source of heat on the ocean floor – but not as much heat as in VMS deposits, and they have high levels of sulphide minerals (galena, sphalerite, pyrrhotite, pyrite) and a banded texture. Copper levels are lower than at VMS deposits because the temperatures of the solutions are lower (150 to 250° C). Volcanic rocks are not present (except in small amounts in a few cases). The host rocks are continental shelf shales, siltstones and turbidites, although carbonates are present in some cases.

Porphyry deposits

Porphyry deposits

Porphyry deposits are the most important ores of copper and molybdenum in BC as well as in the western US and South America. Most porphyry deposits also include some gold, and in a few cases gold is the primary commodity. BC examples include several large deposits within the Highland Valley (southwest of Kamloops), various other deposits scattered around the central part of the province, and the now exhausted Island Copper deposit, at the northern end of Vancouver Island.

Typical features of porphyry and epithermal vein type deposits



Porphyritic intrusions

A porphyry deposit forms around a cooling porphyritic[3] stock in the upper part of the crust. Metal enrichment results from convection of groundwater related to the

[3] The porphyritic texture of the intrusive bodies associated with "porphyry" deposits is indicative of emplacement of the magma at a high level in the crust, and also of a two-stage cooling history.

heat of the stock (figure above). The host rocks, which commonly include the stock itself and the surrounding country rocks, are normally highly fractured and brecciated. During the ore-forming process some of the original minerals in these rocks get altered to potassium feldspar, biotite, and various clay minerals. The important ore minerals include chalcopyrite, bornite (Cu_5FeS_4) and pyrite (in copper rich ores) and molybdenite (MoS_2) and pyrite (in molybdenum rich ores). Gold is present as minute flakes of native gold.

Veins

This type of environment (i.e. around and above an intrusive body) is also favourable for the formation of other types of deposits - particularly vein-type gold deposits. Some of the gold deposits of British Columbia (such as in the Eskay Creek area adjacent to the Alaska Panhandle), and many of the other gold deposits situated all along the western edge of both South and North America are of the *epithermal* type shown in the figure above.

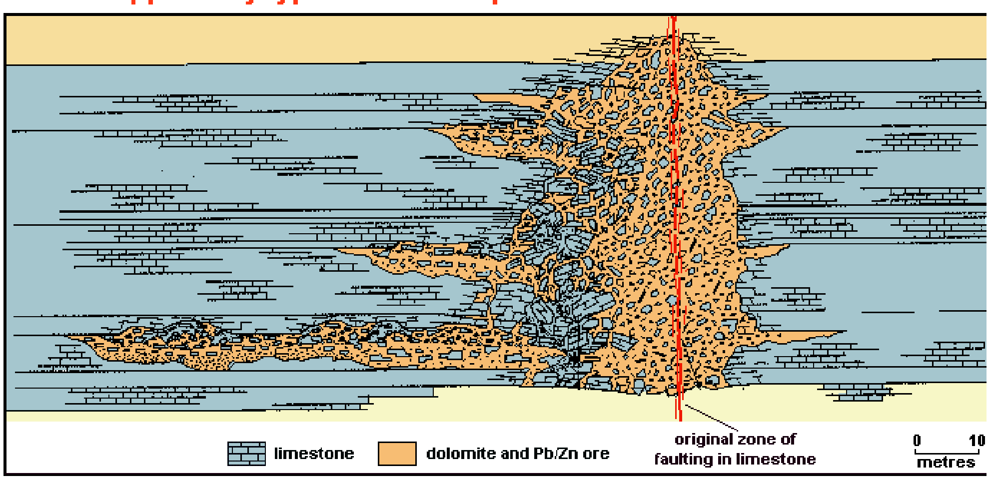
Limestone replacement deposits

Limestone replacement deposits

The so-called *Mississippi Valley Type* deposits are hosted by limestone, and are very important ores of lead and zinc. The most significant Canadian example is the Pine Point deposit south of Yellowknife (now mined out) but there are other similar deposits elsewhere in Canada. The most famous examples are in the Mississippi Valley area of the US.

Typical features of a Mississippi Valley type lead-zinc deposit

Mississippi-Valley type lead-zinc deposit



Almost all Mississippi Valley type deposits are hosted by limestone. Limestone commonly has a high porosity level due to brecciation and solution cavity development (i.e. dissolution) (see figure above). The creation of open spaces in this type of rock may be associated with the process known as *dolomitization*, where the original calcite is transformed into dolomite. The deposits are formed at relatively low temperatures (around 100° C, even lower in some cases) from solutions percolating through the limestone. The ore minerals include sphalerite and galena along with pyrite.

Environ-mental impact of mining

Environmental impact of mining and mineral processing

Mining always involves taking rock out of the ground and exposing it to conditions at surface. The rock is usually crushed and ground and then processed to separate the ore minerals (such as chalcopyrite) from the rest of the minerals. This initial processing normally takes place in a mill at the mine site, and the resulting concentrate is then sent to a smelter where the pure metal is separated out. The waste material from the mill is stored - usually at surface or in a tailings pond, but in some cases in the disused mine openings. Much of the material mined may be of a grade, which is too low to process, and this is also stored - usually on the surface. In some cases some of the waste material is returned to the empty mine adits or to an exhausted open pit.

Acidic drainage and metal contamination

The two environmental issues which are most significant concerning mining are:

1) the exposure of sulphide-bearing rock to surface conditions and the inevitable oxidation of the sulphide minerals to produce acidic drainage, and

2) the potential for escape of toxic materials from tailings enclosures into surface drainages and/or groundwater.

Sulphides in waste rock

Almost all ores contain sulphide minerals, and, as described above, most contain significant amounts of pyrite along with other ore-mineral sulphides. Inevitably a large amount of "waste rock" is mined along with the ore, and while this material may have very low levels of the ore-mineral sulphides, it is commonly quite rich in pyrite. Sulphide minerals are unstable under surface conditions and when they oxidize they react with water to form sulphuric acid. The oxidation is actually enhanced by naturally occurring bacteria including *Thiobacillus ferrooxidans* and others. {for more information see: http://www.osmre.gov/amdform.htm}

Acid mine drainage at the Mt. Washington mine. Copper from the mine has contributed to a significant loss of fish on the Tsolum River.

Heavy metal enrichment

The acidic nature of the water itself presents a serious environmental problem to plants and animals, but mine drainage water can also have very high levels of heavy metals, firstly because some of these are commonly present at relatively high levels in the mine rocks, and secondly because the acidic water is able to dissolve much higher than normal levels of metals just from background sources. These contaminants include lead, arsenic, copper, zinc, cadmium, mercury and many others.

Mine waste

In Canada mine operators are currently required to construct their facilities so that acidic and contaminated runoff can be contained, however in wet climates it can be very difficult to contain all of the water that comes in contact with the ore and waste rock. It is possible to treat acidic water by adding calcium carbonate or lime (CaO) as these will neutralize the acidity, and stabilize many of the heavy metals, but this procedure generates large volumes of sludge, which itself has to be dealt with. Furthermore, the waste piles around a mine may generate acidic drainage for decades after a mine is closed. Firstly, it is expensive to operate treatment plants for such long periods, and secondly there can be little guarantee that mine operators will continue to maintain such plants decades into the future. Other solutions are being used and investigated, including the permanent storage of waste rock in the disused mine openings, and storage under water (in artificial reservoirs), where its reactivity rate will be reduced to near zero.

Tailings ponds

The waste products from a mineral processing facility at a mine (i.e. mill tailings) are normally stored in specially constructed reservoirs, which are designed to ensure that no material leaks or spills into the surrounding environment. Apart from the occasional leak, these structures normally do their job while the mine and mill are in operation, and while regulations demand that they be engineered to last "forever", or else completely decommissioned when the mine is exhausted, it is very difficult to predict what may happen 50 or 100 years into the future. The problem is that many of these facilities contain high levels of heavy metals, plus a very high potential for acidification.

Tailings pond at the Myra Falls Mine (Myra Ck. runs from right to left in the middle distance. The tailings are isolated from the creek by a constructed berm.)

Acid rock drainage in Canada

The acid mine drainage issue is one of the most significant problems facing Canada's mining industry, and while some research money is being spent in an effort to resolve it, there is a very long way to go. At present there are about 740 million tonnes of acid-generating waste rock at mine sites in Canada, plus 12,500 hectares of mill tailings. The estimated cost of dealing with all of this material ranges from $2 to $5 billion. Concern about acid drainage in a pristine wilderness area was one of the primary factors in the provincial government's recent decision to block development of the valuable ($550 million) Windy Craggy deposit in northwestern BC. This decision was a major blow to mining in BC, and it was enough to make many mining companies stop exploration in BC altogether. However, until the acid drainage problem can be solved to the satisfaction of environmental organizations and governments, mining companies can expect to face more of these kinds of decisions in BC and elsewhere in the world[4].

5.2 Energy resources

Energy resources

Canada has abundant energy resources, and - because our energy is relatively cheap, because we are relatively wealthy and because our climate is generally cool - we use more energy per capita than any other country. We have a choice of many different energy options, but almost all of these options have some negative environmental consequences.

Almost all of the energy options discussed below are derived two primary initial sources, (a) the sun, and (b) the energy stored in radioactive elements within the earth (which in turn are derived from nuclear fusion reactions which took place in a pre-existing star).

Hydro

Hydro electricity

In 1985 hydro accounted for 60% of the electricity generated in Canada, and around 95% of the electricity in British Columbia.

The energy recovered in a hydroelectric system is derived from the sun through evaporation of water and precipitation in elevated regions. In some respects it can be considered to be environmentally benign, especially in the rare cases where electricity can be produced without the necessity to construct a dam. Where a dam has to be built (and a reservoir created) in order to provide the hydraulic head necessary to produce electricity, the environmental impact can be significant.

Some of the negative the aspects of hydro-electricity are as follows:

Negative aspects of large hydro projects

- loss of agricultural land and displacement of wildlife and people from flooded areas,
- disruption of geological equilibrium and creation of landslide and flooding potential[5]
- disruption of natural patterns of erosion and sedimentation, which can lead to erosion of sand bars and islands,
- disruption of fish migration routes, and
- release of trace-elements (such as mercury) from flooded areas.
- release of methane from reservoirs if vegetation is not removed before flooding

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[4] Background information on acid rock drainage (ARD) is available at the website of the "Mine Environment Neutral Drainage" (MEND) programhttp://nrcan.gc.ca/mms/canmet-mtb/mmsl-lmsm/mend/default_e.htm The ARD issue is discussed in more detail in Unit 6.

[5] For example, see the description of Vaiont Dam disaster on pages 146 and 147 of Keller. A similar situation exists at Lake Revelstoke, upstream from the Revelstoke Dam. There is potential for catastrophic failure of the Downie Slide, which could result in the over-flow, or even the collapse of the dam just outside of Revelstoke. Steps have been taken to reduce the risk that such a slide will take place.

Fossil fuels

Fossil fuels

In 1985 fossil fuels (primarily coal) accounted for 20% of the electricity produced in Canada, and about 5% of that produced in British Columbia (primarily natural gas in BC). Apart from coal- and gas-fired electrical stations, our primary use of fossil fuels is for transportation (cars, trucks, planes etc.).

Three types of fossil fuels are important - coal, liquid petroleum and gas.

Coal

Coal forms in areas where dead organic material (primarily plant material) can build up to considerable thicknesses in a swampy environment and thus be preserved long enough to be buried [Keller: Figure 15.2]. Without the wet anoxic environment the organic material will become oxidized and will break down. These types of environments exist in slowly subsiding basins of continental interiors and on flat continental margins that are intermittently flooded during periods of subsidence (such as during deposition of the Nanaimo Group). Once the organic-bearing layer is buried and heated up, the process of coalification can take place. This involves dewatering, compaction and the loss of volatiles such as carbon dioxide and methane. The more extreme the conditions, the more pure and carbon-rich the coal will be. The stages of coalification are: lignite, bituminous and anthracite [Keller: Figure 15.3]. Beyond this the carbon will turn into graphite, which is not useful as a fuel.

Environmental impacts of burning coal

Coal is primarily used as a source of heat for production of electricity, but it is also the source of the coke[6] that is used in the steel industry. The environmental effects of burning coal are obvious and considerable. It produces a great deal of carbon dioxide, as well as smoke and ash. Large amounts of sulphur dioxide and nitrous oxide are released, and the former of these contributes significantly to the acid precipitation problem. While some of these environmental effects can be reduced by applying new technologies[7], they cannot be eliminated. Coal also has high levels of many trace metals, including arsenic, selenium, lead, vanadium and uranium. For many of these elements the amounts released through the combustion of coal outweigh the emissions from all other industrial sources combined.

Other aspects of the coal industry

Apart from the negative environmental impact of burning coal, the sheer volume of coal needed to produce electricity is an environmental factor in itself. Hundreds of Canadians have been killed in coal mine accidents, and thousands of others have died early and painful deaths because of the unhealthy conditions

[6] Coke is normally produced by heating bituminous coal so that any remaining volatiles are driven off and the ash is fused with the carbon. It must be strong enough to remain whole during transport.

[7] Various processes have been developed in the past few decades to decrease the environmental impact of coal burning. Firstly the coal can be "washed" prior to burning to reduce the levels of some of the combustion products (such as ash and sulphur). For example, sulphur-consuming bacteria can be used to reduce the sulphur level. Secondly, the process of combustion can be improved so that lower levels of byproducts are released. In **fluidized bed combustion** air is blown through a bed of sand heated to incandescent heat. The coal is introduced and it burns at a lower temperature than normal, the efficiency of combustion is higher, and lower levels of sulphur-dioxide and nitrous-oxide are released. Some of the sulphur can also be captured if limestone is included in the fluidized bed. Thirdly, various technologies (such as "scrubbers") can be used at the post-combustion end of the process, primarily to reduce the amount of sulphur emitted

within coal mines. Even the transportation of coal is an environmental issue because of its huge volume.

Coal bed methane

In recent years there has been a move towards recovery of the abundant volumes of gas (primarily methane) that are present within coal-bearing rocks. While the recovery of coal bed methane has clear environmental advantages (and in many cases economic advantages) over the extraction of coal, it is not without environmental costs.

Oil and gas

Oil and gas are derived from marine organisms deposited along with marine sedimentary rocks (commonly shaly rocks), which, when buried and heated are converted into liquid and gaseous hydrocarbons [Keller: Figure 15.9]. Over time, and given the right geological conditions these hydrocarbons move from one place to another. Hydrocarbon liquids and gases are lighter than water, and hence they tend to move towards the surface through permeable rocks such as sandstone and limestone. Most such materials actually do make it to surface, where the liquids form hydrocarbon seepages (and then become oxidized and destroyed)[8], and the gases are released into the atmosphere. In some cases, however, the hydrocarbons are trapped by some sort of impermeable cap rock, such as shale, and these represent reservoirs of oil and gas [Keller: Figure 15.10].

Oil

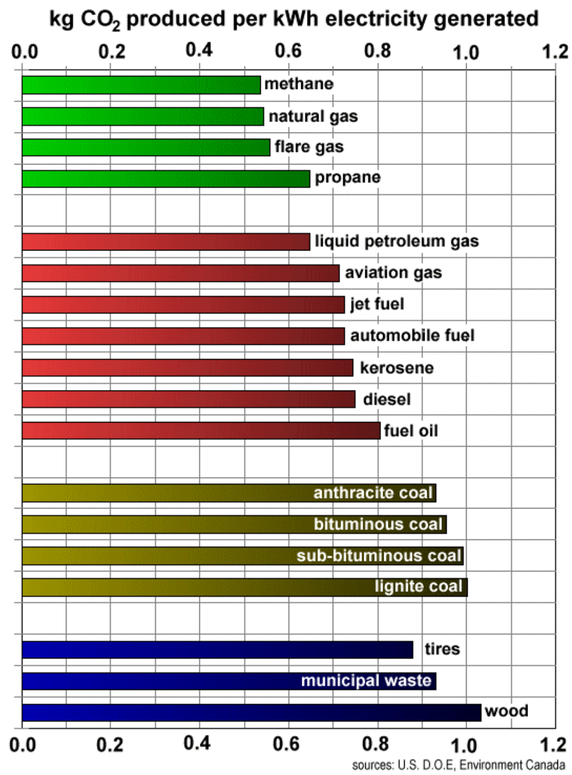
Oil is a complex and variable mixture of relatively large hydrocarbon molecules plus other elements such as sulphur, but it is not as complex nor as dirty as coal, and it can be quite easily processed, refined and transported. Because of its very high energy capacity it is an ideal fuel for vehicles of all kinds. Although it is cleaner than coal it also produces many pollutants, including sulphur-dioxide and nitrous oxide.

Gas

Gas is a mixture of much lighter hydrocarbons (predominantly methane), and it has much lower levels of contaminants, so that it does not pollute as much as oil.

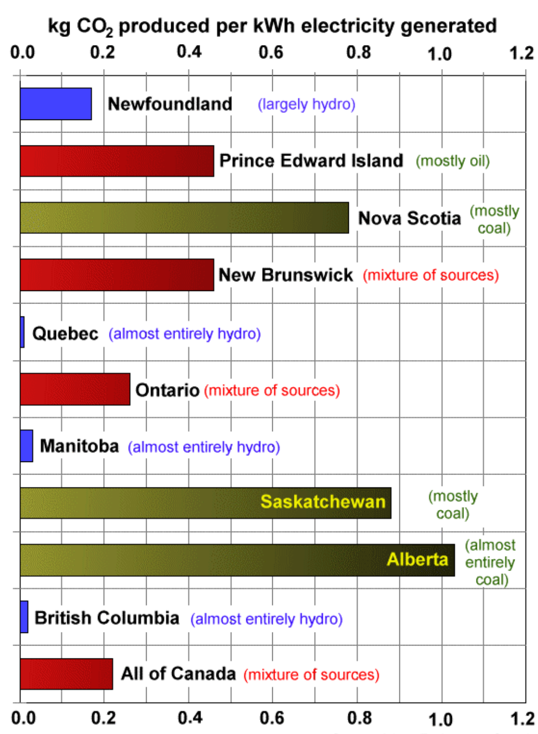
[8] For example, there are large reserves of oil within the sediments of the Gulf of Mexico, and in many areas this oil leaks to the sea floor and then floats up to surface. Oil slicks within these waters are a common and natural feature.

All fossil fuels produce carbon dioxide when burned, but the amount of CO_2 emitted per unit of energy produced varies widely. As shown on the figure to the right, natural gas (primarily methane) produces the least amount of CO_2, followed by the liquid fuels (such as automotive fuel). Coal is the worst of the fossil fuels for CO_2 production, but burning wood is worse still. The CO_2 emission levels of the fuels are generally comparable to their rates of emission of other pollutants, such as nitrous oxide and sulphur dioxide. In other words, natural gas is relatively clean, while coal and wood are dirty.



Carbon dioxide emissions as a function of energy produced for different fuels

Each province of Canada has a different mix of electricity generating activities, and some are relatively "clean", while others are dirty. The provincial rates of CO_2 production as a function of energy produced are given on the figure to the right.



Provincial rates of carbon dioxide emission as a function of energy produced

Nuclear energy

Nuclear

energy

Nuclear energy accounted for 13% of Canada's electricity production in 1985, and the proportion is probably a little higher now. Most of the nuclear generation is in Ontario. None of British Columbia's electricity is derived from this source.

Uranium

At present Canada is the world's largest supplier of uranium, and all of the Canadian production now comes from several mines in northern Saskatchewan. The Saskatchewan deposits were formed at around 1300 m.y. ago. The uranium was dissolved out of rocks such as granite and gneiss and then transported along with groundwater through a large sandstone basin (the 200 by 400 km basin of the Athabasca Group sandstone, which is a very pure quartz sandstone). The water in this basin was largely oxidizing, and hence the uranium stayed in solution until it encountered more deeply circulating groundwater flowing through the underlying gneisses and schists. Some of these older rocks had relatively high levels of reducing agents, such as sulphides and graphite, and thus the deeply-circulating groundwater was strongly reducing. Mixing of the relatively shallow uranium-bearing water within the Athabasca sandstone and the deep reducing water in the older basement rocks led to the precipitation of uraninite (UO_2) at the unconformity between the sandstone and the basement rocks. The Saskatchewan deposits are significantly larger, and at least 10 times higher grade than most of those in other parts of the world.

Nuclear reactors

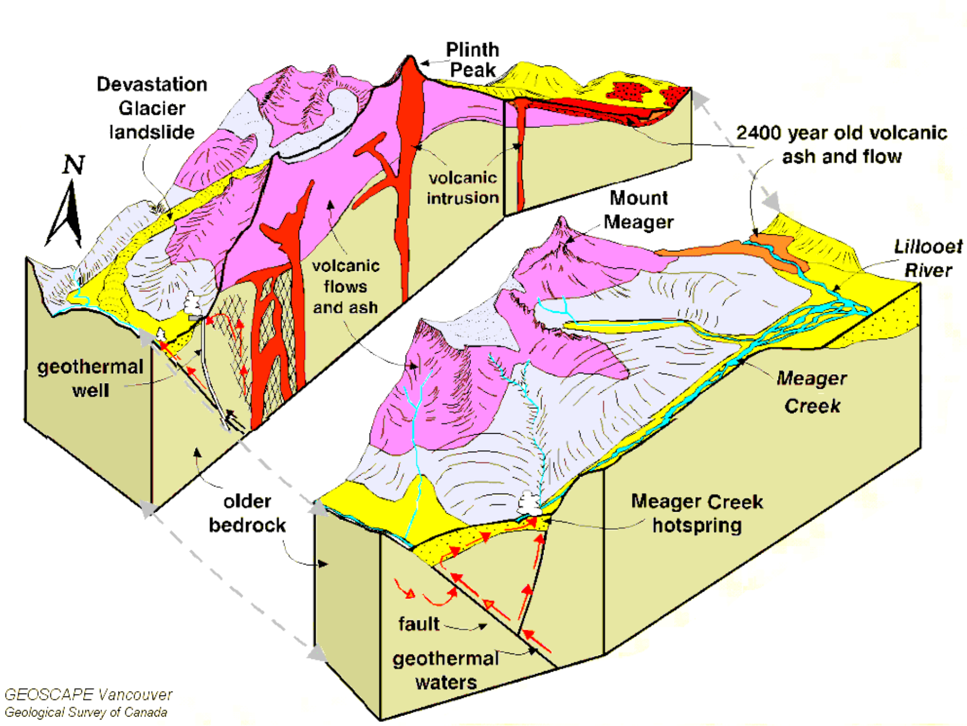
Nuclear reactors do not produce greenhouse gases or other pollution, but they can, if improperly maintained or operated, lead to the release of potentially very dangerous radiation. This is what happened in 1986 at the Ukrainian Chernobyl reactor[9]. Nuclear wastes have a much smaller volume than those produced by thermal plants (e.g. coal), but the wastes are potentially much more hazardous. Perhaps the most difficult of the problems associated with nuclear energy is that some of the materials used by and produced by nuclear reactors can also be used to make atomic weapons.

Geothermal

Geothermal energy

Geothermal energy is used in Iceland, New Zealand, Italy, Japan, The Philippines, Kenya, and United States and in parts of Central America. The primary criterion for the successful use of the earth's heat is that the hot rocks are close enough to surface to be accessed at a reasonable cost. Hot rocks are present everywhere at depths of several kilometres, but it is only in areas where the rocks are at temperatures of well over 100° C within a few hundred metres of surface that this heat can be reasonably used for generation of electricity. This is normally in areas of volcanic activity, but geothermal installations cannot be safely built where there is active volcanism. There is good potential for the development of geothermal energy at Mt. Meagher, north of Whistler.

[9] In official documents 31 deaths and 203 cases of radiation sickness were directly attributed to the Chernobyl accident. We know that the toll was probably much higher than this, and that the health effects will continue to grow. For more on Chernobyl visit this Norwegian website. http://www.bellona.no/imaker?sub=1&id=12663



Cut-away view of the geothermal system at Mt. Meager

Thermal conductivity

One of the limitations of geothermal energy is that a zone of hot rocks is likely to lose much of its heating capacity within a few decades. This is because the cold water that replaces the extracted hot water cools the rocks close to the cracks through which the water flows. While there may still be a lot of heat left in the body of rock, the thermal conductivity of most rocks is very low, and it will then take some time for that heat to be conducted to the zone of permeability.

Ground-source heating

While relatively hot rocks (well over 100° C) are needed to produce electricity, rock and overburden at normal temperatures can be used to assist in the heating and cooling of buildings. The rock and overburden within a few tens of metres of surface normally has a temperature that is equivalent to the average annual temperature at that location (around 10° C for most of southern Canada). In winter water from the ground can be used as a source of heat for indoor heating. The energy cost of using a heat pump to extract heat out of this water is approximately one-quarter that of generating new heat energy by some other means. In summer the same water can be used to cool the air used for air conditioning.

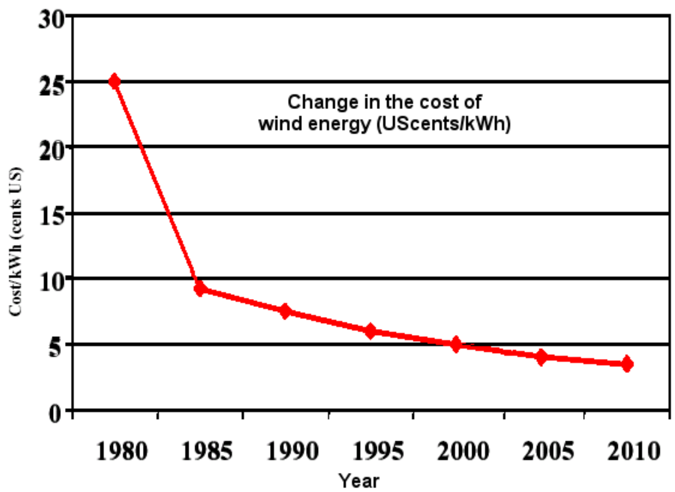
The source of the energy in ground-source heating is the sun, which heats up the ground. Geothermal heat (from below) does not contribute a significant amount.

Other energy sources

Other energy sources

Other sources of energy include solar, wind, wave and tidal energy. While these technologies are not covered in this course, they are our energy future because they are renewable and sustainable, largely non-polluting, sufficiently abundant to meet our needs, and increasingly affordable.

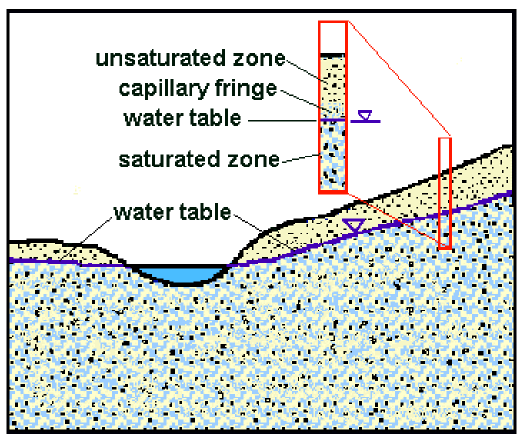
The cost of wind energy, for example, has dropped from more than 25¢ (US) per kWh in 1980 to around 5¢ today. That cost is continuing to drop as wind turbine sizes increase and the installation of wind energy systems continues grow dramatically.



The decreasing cost of wind energy

5.3 Groundwater

If you dig a hole in the ground in a well-drained area you will likely first encounter a layer of moist organic and/or clay-rich soil. You will then pass into material in which the pore spaces are almost all dry (i.e. they are filled with air). This is called the **unsaturated zone**, and it may continue to be essentially dry for a few metres, tens of metres or even hundreds of metres in some dry regions. At some depth the amount of water will gradually increase, and eventually the pore spaces will be completely saturated with water. The line between saturated and unsaturated material is defined as the **water table.**



Relationships between the unsaturated zone, the capillary fringe and the water table

Water table

The zone of increasing water content just above the water table is known as the **capillary fringe**, because the water present here is being held in place by capillary action or surface tension. The water table is an undulating surface that generally reflects the topography - but is more subdued. Below the water table all of the pore spaces in the rock will be filled with water, but as the depth increases the amount of pore space will gradually decrease because of the increasing confining pressure.

Groundwater

What we call **groundwater** includes all of the water from the water table to the depth where there is no longer enough porosity for the rock to hold water. This lower limit will depend on the rock type, but in most cases it will be in the order of a few thousand metres. In terms of a resource, however, the practical limit for groundwater is no more than a few hundred metres, and is usually less. Apart from the difficulty in extracting water from significant depths, deep groundwater

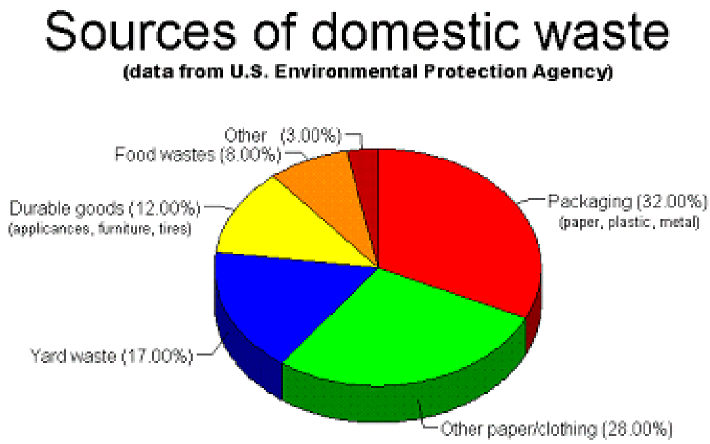
Geological issues in Waste Disposal, Forestry and Engineering

6.1 Waste disposal

From a geological point of view the most important thing about waste disposal is the isolation of the waste, and anything that might leach out of it, from the rest of the environment - particularly from surface and ground waters. The types of waste that we will consider are domestic and industrial wastes (including mine wastes), and wastes from the nuclear energy industry. In all cases we will be concentrating on solid wastes, as opposed to liquid wastes.

Domestic waste

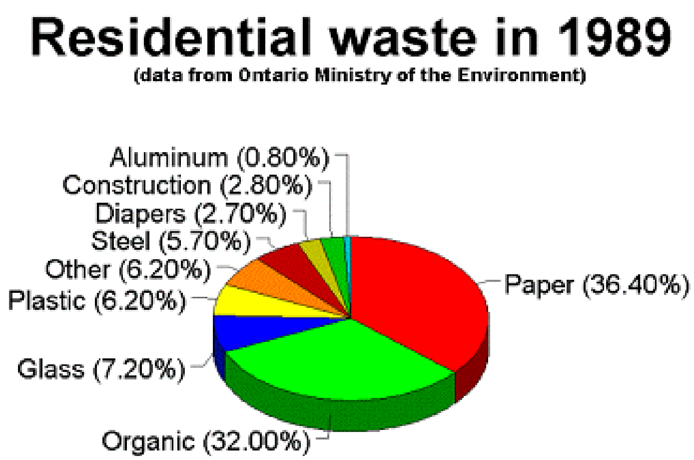
Sources of domestic waste in the United States in 1988



Domestic wastes are what we put in our garbage cans. In Canada each person generates an average of 1.7 kg of household waste per day[1]. This number, which is very similar to that for the US, is roughly twice that of most European countries, and is many times that of most third world countries. In the US the proportions of the sources of domestic waste in 1988 were roughly as shown on the figure above. The proportions in Canada in 1988 were probably very similar.

Composition of domestic waste in Ontario in 1989

A breakdown of the actual materials in domestic waste in Ontario in 1989 is given on the figure below.



In recent years the rates of diversion of some of these materials from waste into recycling programs has increased significantly, and our waste stream now includes a smaller proportion of paper, glass and metal than before.

Anaerobic decomposition

Once it is deposited in a dump or a landfill the waste material starts to break down. Organic material breaks down the most easily - largely through the action of aerobic

[1] In the RDN in 2004 each household generated an average of 30 kg of waste and 12 kg of recycling per month.

bacteria - when the waste is exposed at surface. After the waste is buried anaerobic bacteria continue the process, but the rate is much slower - even for organic matter. Other materials, such as plastic, may decompose at an almost negligible rate when buried.

Metal leaching

Water percolating through wastes will leach out various components, such as heavy metals (arsenic, cadmium, copper, lead, manganese, zinc etc.) nitrate, phosphate and others, and unless this water is recovered (as described below) it could contaminate the groundwater.

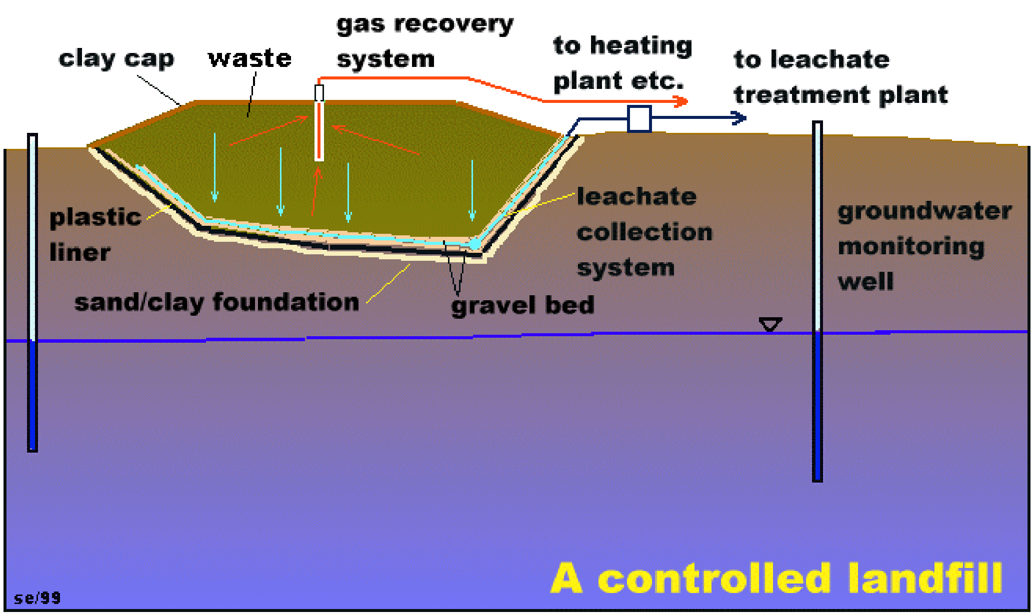
Gases generated

Decomposing waste materials also generate a significant amount of carbon dioxide and sulphur dioxide (from aerobic breakdown) or methane and hydrogen sulphide (from anaerobic breakdown)[2]. Other gases may also be released in small amounts. Again, unless these gases are recovered, they will have an environmental impact - by contributing to the flux of greenhouse gases and to gaseous pollution. The explosive methane can also create a safety problem.

Dumps versus landfills

In the past, municipal wastes were disposed of at dump sites, chosen where there was already a hole in the ground, or where it was easy to dig one. When the dump was full it was covered over and forgotten. Many such dumps are still in use in Canada, but in most parts of the country regulations do not allow new dumps to be constructed (or old dumps to be used for that matter). Instead, wastes must be disposed of in what is known as a controlled landfill.

Schematic view of a controlled landfill



Siting considerations

The primary consideration in the choice of a site for landfill should be the protection of the groundwater supply, but many other factors come into play, such as proximity to the source of the wastes, other uses for the land (agriculture, forestry, wilderness etc.)

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[2] Carbon-dioxide and methane each make up nearly 50% of the gases released at the Cedar landfill (personal communication, Ron McCaw, Regional District of Nanaimo)

and proximity to residences and airports[3].

Preference for a dry climate

In a dry area there may be a wide choice of landfill sites because the water table is likely to be tens or hundreds of metres below surface, and any contamination within the leachate is likely to break down or be adsorbed onto clays and other minerals before it actually reaches the groundwater. Furthermore, with low rainfall, the rate of leaching will be low, and the volume of leachate will be small.

Isolation from groundwater

In a wet area it is important to find a site where the drift (overburden) or bedrock has low permeability. If there is a significant amount of drift, the drift should be clay-rich so that any leachate will move very slowly towards the water table, and the contaminants will be adsorbed. If the drift is thin, the bedrock should have low permeability, with no significant faults or fracture systems.

Landfill liner

In some cases, where the natural conditions are very favourable - such as with thick clay-rich drift, low rainfall and a low water table - it may be acceptable to construct a landfill site with no leachate recovery system, but in most cases it is necessary to create an artificial impermeable barrier beneath the waste, and to extract the leachate for treatment.

The impermeable barrier could be a thick layer of clay, but it should also include a synthetic (plastic) liner. At most landfill sites a combination of these is used, with gravel and sand laid down first, followed by clay, then the plastic liner, then more clay, then more sand and gravel. One of the purposes of the sand and gravel is to protect the plastic liner from the waste, the other is to provide a zone of permeability for the leachate to flow into the drainage system.

Leachate extraction system

Before any waste is put in, a system of pipes and pumps needs to be set up so that leachate that collects at the base of the landfill can be removed. This would normally consist of a network of pipes within a layer of gravel, where, as noted above, the gravel acts as a permeable body to allow the leachate to migrate towards the pipes. The leachate should then be treated to separate the contaminants from the water. Leachate from the RDN landfill at Cedar is pumped into Nanaimo's sewage treatment facility.

Gas extraction system

Once a landfill site has been filled and covered - again with an impermeable layer - the gases given off by the wastes should be removed so that they do not accumulate to dangerous levels. At Cedar, as at most other municipal landfills, these gases contain sufficient methane to be flammable. The gases are captured and, at present, are flared off, although there are plans to use the energy potential of the methane to generate electricity. Even though they are not yet being used as an energy source, its better to burn the gas than to just let it escape, because the methane could be dangerous if it was allowed to escape, and because methane is 21 times more potent as a greenhouse gas than the carbon dioxide that is produced when the methane is burned.

Industrial wastes

Industrial wastes

[3] Waste disposal sites are notorious for their bird populations, and the birds can cause significant problems to aircraft - especially jet aircraft if they are sucked into an engine.

Industrial wastes can be a particularly difficult problem because of their high volume and, in some cases, their significant toxicity. In British Columbia, where there is relatively little manufacturing, and only a small chemical industry, most of our industrial wastes come from the forest and mining industries.

Forest industry wastes

Forest industry wastes

The wastes generated by a pulp mill, include both liquids and solids. The liquid wastes are treated and the post-treatment water is pumped into deep ocean water. According to a spokesperson from the Harmac-Pacific pulp mill in Nanaimo, the water from their operation is non-toxic and contains no organo-chlorines (including dioxin)[4].

Ash, lime and wood waste

The solid wastes from pulp mills include ash from the steam-generating boiler (waste wood products are used to heat the boiler), lime waste (CaO from the calcining plant) and wood waste. These materials are typically placed in an on-site land-fill. Because of the significant quantity of lime in the waste the leachate is normally quite alkaline (as compared with the mildly acidic leachate at a typical domestic landfill). There are monitoring wells around the landfill, and Harmac-Pacific is required to test the water several times a year and provide the results to the environment ministry. The Harmac landfillis not lined.

Mining industry wastes

Acidic drainage and metal contamination related to mining

Almost all types of mining, including metal mining and coal mining, and even some quarrying, or rock excavation related to construction, result in the exposure of sulphide minerals (especially **pyrite**) to the oxidizing surface environment. Oxidation of the sulphides leads to the generation of strongly acidic drainage water. Such waters commonly also have high levels of metals.

The following strategies can be used for minimization and treatment of acid drainage.

Predicting acid drainage

Prediction: Prediction of the acid-producing potential of a mining or excavation project is essential in order to be able to design appropriate mitigation facilities and procedures. The sulphide content of the waste rock must be assessed, and the nature of the sulphide minerals, including factors such as mineral type, grain-size, distribution within the rock, should be studied. The content of any alkaline-producing minerals (such as calcite) must also be considered as these can help to reduce the acid problem. Theoretical models may not be adequate in many cases, and experimental studies should be carried out using representative samples of the actual material that will be exposed.

Isolating acid-producing materials

Isolation: In some cases it is possible to isolate the acid-producing materials from the air and/or water of the surficial environment. Oxygen has a very limited solubility in water, and if the wastes can be stored in a stagnant (or very low flow) sub-aqueous environment, the degree of oxidation can be kept to a manageable low level. This can be

[4] Personal communication, Mr. Bart Howie, Harmac Pacific's environmental division, Nanaimo, spring 1998

done at surface within a constructed holding pond[5], within an exhausted open pit, or within mine tunnels and shafts that would then be flooded. The use of flooded mine openings is not necessarily a straightforward solution, especially in high-relief areas, where the flow of oxidizing water is still likely to take place. The advantage of sub-aqueous isolation is that as long as it is well designed the facility should last for an indefinite period, and thus the ongoing costs will not be excessive.

Isolation of mine wastes in a dry environment above the water table - using clay caps - is also a possible solution, but in practice it would be very difficult to ensure complete isolation of the material, especially over a period of many decades.

Treating acidic drainage

Treatment: In most cases it is necessary to use alkaline treatment techniques to neutralize acid drainage and to promote precipitation of heavy metals. Various reagents can be used, depending on the severity of the problem. The simplest and least expensive treatment is with limestone (calcite), however this is only effective for solutions with relatively low acid levels[6]. Hydrated lime (Ca(OH)2) is the most commonly used agent for neutralizing acidic drainage because it is safe to handle and effective with high-strength acidic solutions. Hydrated lime must be produced from limestone ($CaCO_3$), and this represents a significant cost (and also an environmental cost because it involves heating and release of carbon dioxide to the atmosphere). Furthermore, treatment with lime it produces a high volume of very wet sludge, which becomes a disposal problem in itself. Other reagents used for neutralization include sodium carbonate, sodium hydroxide and ammonia. These are relatively high cost solutions, and the reagents are dangerous to work with. In the case of ammonia the downstream environmental effects (nitrification and toxicity to fish) can be significant.

Artificial wetlands

A relatively new concept for the treatment of acid runoff (as distinct from the acid-generating material) is the use of artificially constructed wetlands (ie artificial bogs). In this type of environment natural micro-organisms and plants can neutralize and remove metals from waste solutions. The primary advantage would be that the facility should be capable of operating indefinitely with little maintenance.

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[5] In fact natural swamps, ponds and small isolated lakes would probably be ideal for this type of isolation because they are already full of natural organic reductants and there is a continuing supply from the surrounding environment. It is very unlikely, however, that the environmental community would accept the concept of dumping mine waste into a natural drainage basin.

[6] Acidity is expressed in pH units, but the strength of the acid solutions is also an important factor. A dilute solution of acid (such as acidic rain) can have a low pH, but it would take the addition very little alkaline material to balance that pH. A concentrated solution with a similarly low pH would require much more alkaline material to reach a neutral pH. Solutions with acidities exceeding 50 mg/L cannot be effectively treated using limestone.

Waste treatment at the Myra Falls operation

The Myra Falls mine

Since 1966 a large and profitable copper, lead and zinc mine (volcanogenic massive sulphide deposit) has been operated at Myra Falls, near to the southern end of Buttle Lake, within Strathcona Park, Vancouver Island[7]. The mine is actually within a special part of the park, and has been allowed to continue operation because it was discovered before the park was established.

Disposal of mill tailings into Buttle Lake

From 1967 to 1984 mill tailings were deposited within Buttle Lake beneath 30 m of water, and waste rock was piled up adjacent to the mine. During the late 1970's the provincial environment ministry discovered that lake water in the area of the tailings disposal had zinc levels of over 0.1 mg/l, as compared with the background level of 0.01 mg/l. The company was ordered to stop dumping their waste into the lake and develop an on-land tailings disposal facility, which they did.

Metal contamination from waste rock

It was subsequently discovered that the elevated zinc levels in the lake were not derived from the tailings stored under water, but from the leaching of the waste rock stockpiled near to the mine, 2 to 3 km up Myra Creek from the lake. It was also shown that the conditions around the in-lake tailings were consistently reducing, that the deposited materials were stable, and would probably become more stable as they became covered with additional organic lake sediment.

Underground disposal

At present between 50 and 60% of the mill tailings at Myra Falls is mixed with cement and used to fill mine openings that are no longer needed. The remainder, which is about 50% solids and 50% water, is discharged using spraybars onto a "dry" tailings deposit. The water collects in a pond and is treated. The solids build up in thin (30 to 50 mm) graded layers, and the uppermost fine material provides a nearly impervious barrier to natural precipitation.

Lime treatment of waste water

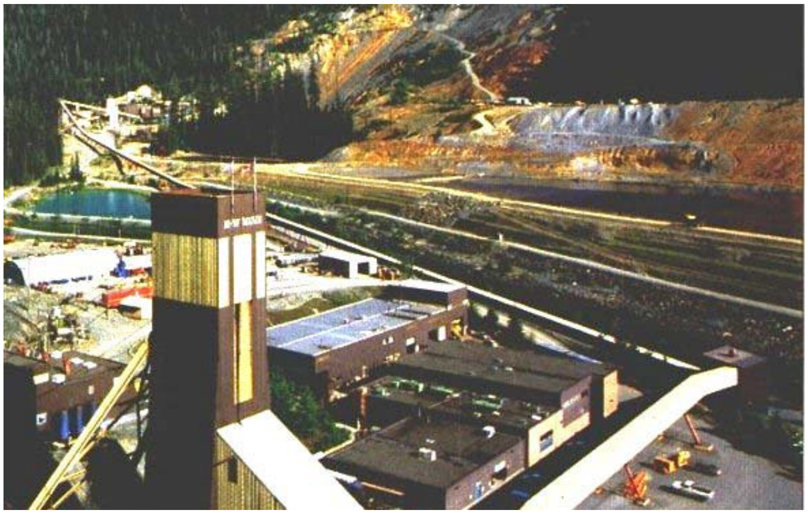
The waste rock is now stored in an area where its leachate can be recovered, and this liquid, along with the water from the tailings area, is treated with lime to increase the pH and promote precipitation of metals. Some of the treated water is recycled back through the mill, and the rest is released into Myra Creek once it has been ascertained that it meets strict trace-element limits, and passes a bio-assay test. For the bio-assay 10 fingerling Rainbow trout must survive for 96 hours in the undiluted effluent water. The water in Myra Creek, and in the adjacent area of Buttle Lake now has very low levels of zinc and other metals. The mining company monitors lake and stream water chemistry at various locations within the Campbell River drainage system, from adjacent to the mine, to just outside of Campbell River itself.

Once the Myra Falls deposits have been exhausted, as much of the waste rock and tailings as possible will be returned to the underground mine openings. The rest will be sealed over in a dry storage facility, and the area will be re-vegetated[8].

Part of the Myra Falls operation is shown on the figure below. The waste-rock pile is visible in the background, and the tailings pond is situated immediately in front of this.

[7] For most of its life the mine was operated by Westmin Resources Ltd. In 1999 Westmin was taken over by the Swedish-Canadian mining company Boliden.

[8] Information on the Myra Falls tailings and waste rock disposal system has been provided by Steven Januszewski, Environmental Engineer for Boliden at Myra Falls



Note the rusty colouration of much of the rock in the background. Most of this is a product of oxidation of sulphide minerals in the rocks. Myra Creek runs between the tailings pond and the complex in the foreground, which includes the headframe of the mine. The figure below shows the same area from the opposite direction.

The Myra Falls mining operation in Strathcona Park

(the headframe is the structure that houses the elevator to transport miners, equipment materials, waste rock and ore into and out of the mine)

Looking across the Myra Falls waste-rock pile (foreground) and tailings pond. Myra Creek runs between the tailings pond and the headframe (back right)

Nuclear wastes

Disposal of waste from nuclear reactors

Wastes from nuclear power plants represent a particularly difficult problem because of their potentially high toxicity and very long life. The actual nature of the wastes is dependant on the type of reactor system in use, but typical components include ^{239}Pu (plutonium), which is highly toxic, and ^{90}Sr (strontium), which can substitute for the calcium in bones and thus can be very dangerous. ^{239}Pu has a half-life of 24,000 years, and if we accept the standard that radioactive wastes should be isolated from the surface environment for at least 10 half lives, then we are faced with the need to store these materials safely for 240,000 years! [9]

[9] After 10 half-lives approximately 0.1% of the original radioactive nuclide remains

At present radioactive wastes are typically stored in large water pools adjacent to nuclear reactors. After several years in one of these pools the wastes are sufficiently "cool" so that they can be stored dry within large concrete containers. These facilities are safe, but it is obvious that this is no long-term solution. While a number of imaginative disposal ideas have been suggested - such as sending the wastes into space, or letting them melt their way down to the base of the Antarctic ice cap, or allowing them to be subducted along with oceanic crust, most people working in this field feel that the most practical solutions involve storage within solid rock deep within the continental crust.

Short-term storage of nuclear wastes

In Canada the most likely location for nuclear waste disposal would be within the old rocks of the Canadian Shield[10]. The concept is that the waste material should be secured within a system of multiple barriers, as follows:

Storage of Canadian nuclear wastes

1. the radioactive material would be immobilized into ceramic or glass composite pellets - materials which are highly resistant to leaching by water,
2. the pellets would be surrounded by absorptive substances (such as bentonite clay) and then enclosed in corrosion-resistant (eg. titanium alloy) canisters,
3. the canisters would be buried within a clay-rich backfill medium in holes drilled into solid rock at a depth of around 1000 m, and
4. eventually the depository would be filled in and sealed.

The theory behind this concept is that the rocks of the shield are not going to be subject to major tectonic forces for many millions of years, and that groundwater flow rates at depth within such rocks are very slow. In many places deep groundwater has been shown to be in the order of millions of years old (ie. it has been isolated from the atmosphere for millions of years). This is especially true in the low relief parts of the shield where the regional hydraulic gradients are commonly less than 1 metre per kilometre. If the granitic and gneissic rocks of these areas are generally unfractured, their permeability levels will also be very low. See the following box for an estimation of the rate of flow of groundwater deep in the rocks of the shield.

Deep groundwater flow rates in rocks of the Canadian Shield

In the Canadian Shield it is not uncommon for the regional slope, and hence the slope (i) of the water table, to be less than1 m per km (<0.001 or 10^{-3}). An unfractured granite may have a permeability (k) of 10^{-8} cm/sec. Using Darcy's law, we can estimate the groundwater flow rate to be:

$$v = ki$$
$$v = 10^{-3} \times 10^{-8} \text{ cm/sec}$$
$$v = 10^{-11} \text{ cm/sec,}$$
$$v = 3 \times 10^{-6} \text{ m/year}$$

or 3 metres in one million years.

The concept of nuclear waste disposal within the shield has been demonstrated at a test site within the Lac du Bonnet granitic pluton at Pinawa, east of Winnipeg, and the next step in the process is to find a suitable and acceptable site within Ontario, where most of Canada's nuclear waste is produced. As in all waste disposal issues, one of the

Nuclear waste demonstration site

[10] Atomic Energy of Canada Limited (a federal agency) is responsible for developing nuclear waste disposal in Canada. The work that they are doing is described at their website: http://www.aecl.ca/index.asp?menuid=500&miid=544&layid=3&csid=301

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